FINAL REPORT

Title: Trial by fire: community adaptation and rebuilding after catastrophic wildfire

JFSP PROJECT ID: 14-2-01-6

March 23, 2020

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List of Abbreviations/Acronyms

CWPP: Community wildfire protection plan
FAC: Fire adapted community
FHSZ: Fire hazard severity zones
WUI: Wildland-urban interface

Keywords

Firewise, planning, risk, WUI, recovery

Acknowledgments

We gratefully acknowledge support for this work by the Joint Fire Science Program and the Rocky Mountain Research Station and Northern Research Station of the USDA Forest Service. We also acknowledge the Forest Research Center, which is a research unit funded by Fundacao para a Ciencia e a Tecnologia I. P., Portugal (GrantUID/ABR/00239/2013). We are indebted to all interviewees for sharing their knowledge with us. We thank our collaborators Patricia Alexandre, Van Butsic, Hillary Fishler, David C. Helmers, H. Anu Kramer, and Carlos Ramirez-Reyes for their contributions to this project. C. Armer, A. Bontje, J. Canfield, A. Ciurro, B. Fendt, C. Frederick, S. Gordon, J. Paulson, T. Ng, K. Thomason, and C. Trott all assisted with data collection.

Abstract

Wildfire losses in the U.S. have soared over the past several decades, as residential development in fire-prone vegetation has expanded, causing more ignitions and creating a vast wildland-urban interface (WUI) to protect during fire. However, wildfires themselves may be valuable opportunities for adaptation. The highly dispersed and variable nature of WUI communities, in addition to the locally-driven character of post-fire responses means that it is challenging to understand wildfire impacts and outcomes. Accordingly, we examined the outcomes of destructive wildfire over multiple spatial and temporal scales, using social and biophysical data. Our objectives were to evaluate community-level policy change and adaptation after wildfire, examine changes in the built environment and building-level exposure over time, and assess how wildfire losses relate to broad policy and outreach definitions.

For our first objective we used a case study approach to investigate post-fire community-level mitigation in eight study sites across the US that had experienced wildfire in 2009 and 2011. Five years post-fire we found many communities had pursued additional mitigation, but focusing on efforts that readily gain public support, such as enhancing suppression, education, outreach, and hazard planning. Such action was most common when destructive wildfire was novel and there was local government capacity to capitalize on this occasion. Local governments in our study sites largely declined to pursue land use planning to restrict or otherwise guide development after a destructive wildfire.

Evaluation of built environment post-fire similarly suggested that wildfire experience does not consistently lead to adaptation. A digitized dataset of California wildfires (1970-2013) shows that destructive wildfire resulted in few buildings being permanently removed from the landscape, new development was substantial, and neither rebuilding nor new construction indicated consistent adaptation through better building placement, short- or long-term. In fact, long-term, in approximately half of the wildfires, building-level risk actually increased over time with new development (four out of nine fires). Given these challenges in adapting to wildfire threats, this study highlights the value of spatially explicit data on wildfire losses and recovery over time. For our final objective we demonstrated that wildfire losses are occurring within and in close proximity to WUI as it is mapped, both nationally and for the state of California.

Ultimately, continuing to track and investigate wildfire outcomes will be invaluable to assess wildfire policy and provide a path towards wildfire risk reduction. Future research could integrate data on wildfire losses with other building- and individual-level risk mitigation actions to build a fuller picture of post-wildfire adaptation. We conclude that successful examples of community wildfire risk reduction in a range of settings post-fire, including land use planning, , will be essential to increasing effective community adaptation, particularly for fire-affected communities where housing is already extensively developed, destructive wildfire is commonplace, and/or interest in adaptation and capacity for using formal tools and actions is low.

Objectives

This project included three research objectives, and all objectives were met. We added an additional objective (D) which emerged during our research.

Objective A) Community-level policy change and adaptation after wildfire. Community-level efforts to reduce wildfire risk can include a diverse range of efforts, such as revising land use planning and regulations, pursuing fuel treatments on public and private land, or promoting informal/voluntary efforts such as education campaigns. The time after wildfire may be a unique opportunity for communities to both evaluate past efforts and consider new ones, but it is unclear if wildfire disasters spur such community-level change. Our goal was to determine what regulatory and informal/voluntary community-level changes were pursued in eight study sites across the conterminous U.S. We related these changes to site characteristics and examined officials' perceptions of land use planning to reduce wildfire exposure.

Objective B) Investigate rebuilding and new construction after historical wildfire events. Using digital imagery and public records, our goal was to map historical wildfires and create a long-term GIS database of buildings lost, rebuilt, and newly built (i.e., locations where buildings only appeared post-fire). Given the limited availability of digital imagery we focused on wildfires in California from 1970 onwards, for which at least 20 buildings were lost. We used these data to determine the rate and extent of rebuilding and new development post-fire, both for short (3-6 years) and long timeframes (up to 25 years).

Objective C) Analyze wildfire risk for post-fire development. Using our data on rebuilding and new development post fire (Obj. B) we analyzed the wildfire risk associated with locations for new and rebuilt buildings. We used statistical models to examine the average risk of built locations over time. An increase in average building risk post-fire suggests a lack of adaptation in building placement and potential for future wildfire exposure.

Objective D) Analyze spatial patterns of wildfire losses relative to policy and outreach. As this research study progressed, questions emerged regarding the spatial patterns of buildings lost to wildfire, and how these losses relate to current policy classifications and outreach programs. We focused on national and state-level policy designations and outreach programs. We looked at national losses across the conterminous U.S. (2000-2013) and those in California over a longer time frame (1985-2013).

Background

Wildfire management in the United States has become increasingly challenging and costly over the past two decades, as residential development in fire-prone vegetation has expanded, causing more ignitions and creating more infrastructure to protect during fire (Balch et al. 2017, Radeloff et al. 2018). According to the US National Interagency Fire Center (2017), wildfires destroyed on average 1,545 houses per year between 1999 and 2017; however, the last two years were well in excess of this average, with record-breaking events in Northern California—more than 8,000 houses destroyed in 2017 (National Interagency Fire Center 2017) and nearly 20,000 houses destroyed in 2018 (Insurance Information Institute 2018). In the future, wildfire management will likely become more challenging due to a changing climate, the cumulative impacts of fire suppression, and continuing wildland-urban interface (WUI) expansion (Flannigan et al. 2013, Moritz et al. 2014).

In response to the challenges of wildfire management, the National Cohesive Wildland Fire Management Strategy advocates the creation of fire adapted communities (FAC) that can coexist with wildfire through education, fuel treatments, planning and management of the built environment, and appropriate suppression and emergency response (Fire Adapted Communities Coalition 2014). Much of this effort focuses on the wildland-urban interface (WUI), that area where homes are intermingled to or adjacent to wildland vegetation (USDA and USDI 2001, Radeloff et al. 2018). Ideally, local governments, residents, and partners will collaborate to reduce wildfire risk, revising programs and actions over time to keep pace with emerging concerns (Fire Adapted Communities Coalition 2014).

For example, public land managers can thin vegetation or use prescribed burns to reduce the likelihood of wildfire spread onto private lands (Winter et al. 2002, Stephens et al. 2012). Homeowners can select fire-resistant materials for their homes and mitigate vegetation around their residences (i.e., create defensible space) to lower the risk of loss to wildfire (Cohen 2000, Mell et al. 2010). Local government also plays an important role through a variety of mechanisms. Residential mitigation (home materials or vegetation) can be encouraged via education and outreach programs or required by a variety of mechanisms, such as building codes, overlay zoning, and other ordinances or regulations (Winter et al. 2009, McCaffrey et al. 2011, Mowery et al. 2019). Governments can also guide or restrict residential development to minimize wildfire risk, and incorporate wildfire risk into community planning (Fire Adapted Communities Coalition 2014, FAC Learning Network 2016). This responsibility falls to local governments because unlike other natural hazards (e.g., floods), there are no federal mandates to minimize or manage wildfire exposure (Burby 2001, Thomas and Leichenko 2011).

However, given the range of potential actions for wildfire risk reduction and the diversity of communities in the WUI (Paveglio et al. 2015), it is unclear how current policies (e.g., WUI designations) relate to losses or how communities will transition toward the FAC goal of living with fire on the landscape. As currently envisioned, a fire adapted community initiates changes iteratively in response to destructive fires and risks, using a broad range of tools and actions to diminish wildfire exposure (Fire Adapted Communities Coalition 2014, FAC Learning Network 2016). ***This research effort focused on the relationships between wildfire policies and outcomes, emphasizing wildfire experience and recovery as a key opportunity for learning and adaptation at the community level.***

Our emphasis on wildfire experience emerged from the broader hazards literature which has shown that hazard events can trigger periods of learning and adaptation, opening a "window of opportunity" for changes in policy and practice (Kingdon 1984, Solecki and Michaels 1994, Birkland 2006). Indeed, there is some evidence of adaptive change after wildfire as well: for example, regulations about home mitigation (materials and vegetation) are often adopted after wildfires (Duerksen et al. 2011). However, like other hazards, wildfires do not always lead to widespread change that reduces future exposure, and responses may even exacerbate future risk. Local governments may not revise land use planning to minimize hazard exposure; instead, recovery programs may stimulate rebuilding and new development in hazard prone areas (Platt 2002, Pais and Elliott 2008, Mockrin et al. 2016). In an analysis of the conterminous United States, rebuilding and new building inside wildfire perimeters in the five years after fires was variable, but in some cases prolific (Alexandre et al. 2015). It was not uncommon for more buildings to exist within a wildfire perimeter five years after a wildfire, in large part due to new building within fire perimeters (Alexandre et al. 2015). Such an increase of people and buildings in flammable areas will exacerbate wildfire exposure by increasing both assets that could be lost (number and value of buildings), as well as ignitions, which are often human-caused (Syphard et al. 2007, Syphard et al. 2017). However, these studies did not consider building-specific risk and position on the landscape, nor consider longer time frames.

Despite the importance of understanding wildfire experience, hazards recovery research has focused on other hazards such as floods, earthquakes, and hurricanes, which are typically larger than wildfires (Schumann III 2020). Research on wildfire impacts has focused on residents (risk perception, mitigation, evacuation experiences, etc.), not policy outcomes or changes in the built environment post-fire. Although wildfires have become more common and destructive across the U.S., the responsibility for adapting to this threat remains dispersed, falling primarily to local governments and informal institutions at the community level, making it challenging to track and understand adaptation. Even policies that extend beyond the local level, for example, national or state level maps of wildfire hazard or WUI are rarely evaluated to determine if they are adequately capturing the homes and areas most likely to be damaged by wildfire.

Accordingly, this study examined destructive wildfire and related policies and outcomes in several ways. We conducted case study research in eight locations across the United States in order to better understand local policy change post-fire (Objective A). We mapped and analyzed the rebuilding and new development post-fire for California (1985-2013), and considered the potential risk of post-fire building locations, both over short- and long-time frames (Objectives B, C). Finally, we also examined wildfire losses in relation to current policy classifications (e.g., wildland-urban interface, fire hazard severity zones) and wildfire outreach programs (Objective D). In combination, these objectives offer new insight into WUI losses and recovery, and suggest avenues for adaptation in fire-prone communities.

Materials and Methods

Objective A-Community-level policy change and adaptation after wildfire

We selected eight sites with a range of socioeconomic, environmental, and governance characteristics (Figure 1, Table 1); for more detail on each fire and community please see Appendix C. We chose locations across the U.S., including two sites in the Southern Great Plains and one in the Southeastern U.S, to expand beyond the commonly-studied Western U.S. We selected fires that occurred in 2009 and 2011 where at least 20 homes were destroyed by fire. We chose these years to allow time for any community-level changes to develop before interviews (no fires in 2010 met the damage criteria). In one case (the Monastery Fire in Washington state), the number of homes reported lost was later determined to be less than 20, but respondents were still able to characterize the fire event and response, so we retained the site in our study (Appendix C).

We collected background information from media sources and government documents, and then interviewed local officials and community leaders. For both interviews and document review, we chose jurisdictions where most homes were lost (typically counties, although in two cases where fires spanned city and county boundaries, we surveyed both locations) (Table 1). We used document reviews to assess formal (governmental) investment in wildfire-related regulations and planning prior to focal wildfire events. We compiled a list of wildfire-related regulations and planning actions recommended in guides for communities (NFPA 2013, Fire

Adapted Communities Coalition 2014). For more information on document review please see Mockrin et al (2018).

During interviews we confirmed the document review results and examined wildfire history, damages, and resident risk perception and mitigation actions, in addition to background information on community-level change (e.g., changes considered but not pursued). In total, we interviewed 80 people, including county and city government staff (planners, emergency managers), fire chiefs, state and federal government employees (foresters, natural resource managers, fire managers), university extension agents, real estate agents, and other community leaders who were actively involved with wildfire recovery and mitigation (e.g., head of a civic association, point person for a neighborhood). Research protocols were approved by the Human Research Protection Program and Institutional Review Board of Oregon State University. Informed consent was obtained from all individual participants included in the study.

Interviews took place between December 2014 and November 2015 (on average 5 years after fires), with 6-12 informants per site, and three to seven days spent per site. We identified central informants, typically fire department or government staff, through government documents, web searches, or newspaper articles about the fire. These key informants then suggested others we should speak with. Interviews were typically 1-2 hours, conducted individually or in small groups (maximum of four) when more than one person from the same organization was interested in participating (e.g., multiple members of a planning department). We used the same set of open-ended, semi-structured questions for all interviews, expanding upon questions developed by Mockrin et al. (2015). For our first fieldwork visit, all three authors conducted interviews together, revising interview questions as needed. Subsequent visits were conducted by one or two investigators. Interviews were conducted in person if possible, with several interviews held over the phone.

After professional transcription, we used open coding to organize concepts into initial categories, followed by focused coding to organize material into themes (Corbin and Strauss 2015), working in QSR Nvivo 11 software (QSR 2014). Authors worked together to generate initial themes, and Mockrin then conducted coding. Our analyses focused on documenting the community-level adaptation actions pursued, determining how these efforts related to characteristics of communities and local government, and location government staff perceptions of land use planning and regulations to reduce wildfire risk. For more information on methods and analyses, see Mockrin et al (2018, 2020).

Figure 1. Map of study sites across the United States for Objective A

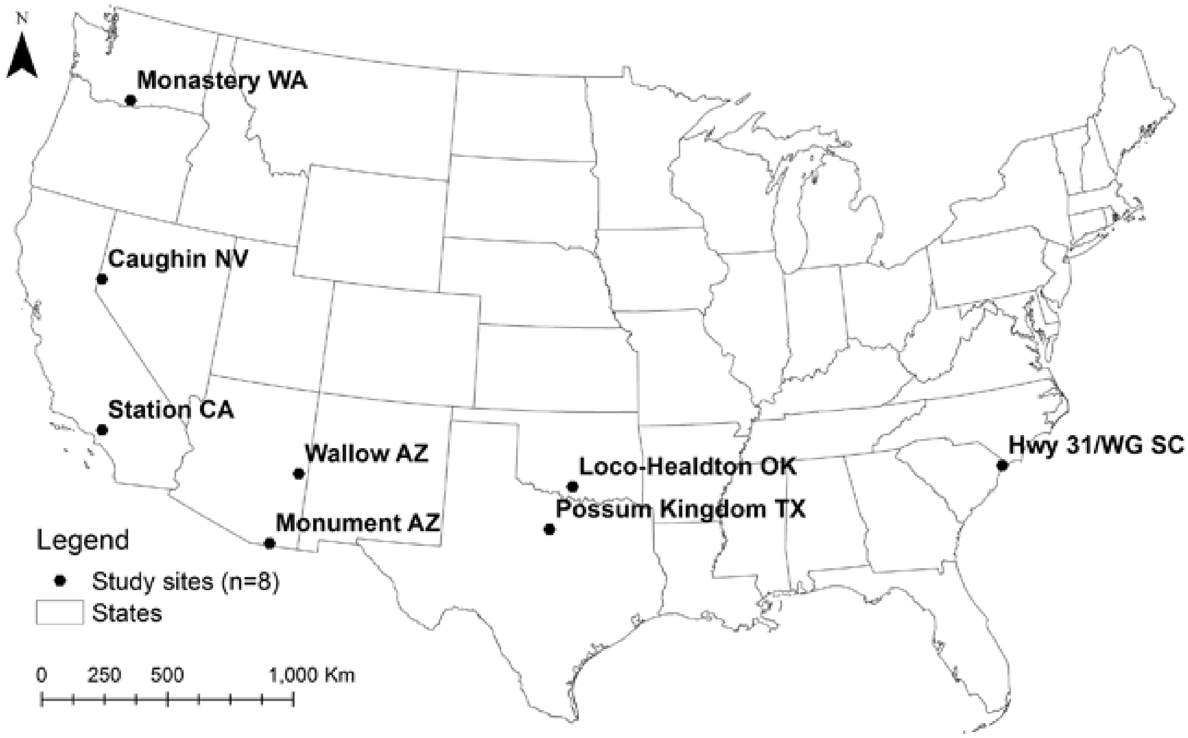


Table 1. Characteristics of study sites and focal wildfires (n = 8)

Site	Jurisdictions	Fire year	Prev. fire experience[a]	Formal wildfire regs. and planning[b]	Economy base[c]	Political orient.[d]	Urban typology[e]	Median income, 2010	% in poverty 2010
Caughlin NV	Washoe County; Reno	2011	No	High	Services	Dem	Small metro	$67,177	12%
Hwy 31 / WG SC	Horry County; North Myrtle Beach	2009	No	Med	Services	Rep	Small metro	$51,691	15%
Loco-Healdton OK	Stephens and Carter Counties	2009	Yes	Low	Mining	Rep	Nonmetro	$49,558	15%
Monastery WA	Klickitat County	2011	No	Med	Manufacturing	Rep	Nonmetro	$46,340	20%
Monument AZ	Cochise County	2011	No	Med	Federal/State Govt	Rep	Nonmetro[f]	$52,513	16%
Possum Kingdom TX	Palo Pinto County	2011	No	Low	Non-specialized	Rep	Nonmetro	$48,584	14%
Station CA	Los Angeles County	2009	Yes	High	Services	Dem	Large metro	$60,879	15%
Wallow AZ	Apache County[g]	2011	Yes	High	Federal/State Govt	Dem	Nonmetro	$35,059	37%

[a]Determined through interviews
[b]McGranahan, DA (1999) 'Natural amenities drive rural population change. Agricultural Economic Report No. 781.' US Department of Agriculture, Economic Research Service: Washington DC
[c]Economic Research Service, 2004 County Typology Codes. http://www.ers.usda.gov/data-products/county-typology-codes.aspx
[d]From 2012 presidential election
[e]Economic Research Service, 2003 Urban Typology Codes. http://www.ers.usda.gov/data-products/urban-influence-codes.aspx
[f]Since reclassified to small metro
[g]This was a large fire, but buildings were lost primarily in Apache County

Objective B) Map rebuilding and new construction after historical wildfire events
We collected data on destruction, rebuilding, and new construction in wildfires that burned between 1970 and 2009 in California. We chose this timeframe and state so that we had enough imagery available and there was sufficient time since wildfire to assess rebuilding and new development. In total we compiled data for 28 fires: 11 fires that occurred prior to 2000 and 17 fires that burned between 2000 and 2009. For the fires prior to 2000, data was collected for this research effort and methods are described below. For data after 2000, we selected fires from a pre-existing dataset, with methods described by Alexandre et al. (2015) and Kramer et al. (2018).

Data for historical wildfires (n=11) were created by searching databases for reports of wildfires that destroyed numerous buildings. We searched assorted newspaper archives, CAL FIRE's list of the top 20 most destructive wildfires (CAL FIRE 2018), the USDA Forest Service national database of destructive wildfires (Short 2014), Incident Command Status (ICS-209) reports, which compile daily records of building damage for wildfires where these reports are generated (National Wildfire Coordinating Group 2016), and National Interagency Fire Center's data on historically significant wildland fires (National Interagency Fire Center 2016). Based on these databases, we identified candidate wildfires, and searched for wildfire perimeters from state and national databases. We then collected aerial photographs and high-resolution satellite images over time, up to 25 years after fire, from a variety of sources including Google Earth (Google Inc. 2016), UC Santa Barbara's aerial photo library (UC Santa Barbara Library), a national database of aerial images (Nationwide Environmental Title Research LLC.), and library archives at University of Wisconsin-Madison.

We georeferenced the images and digitized the location of every building within the wildfire perimeter and up to 500 m outside of it to account for potential inaccuracies in perimeter mapping and the chance of spot-fire ignitions outside the mapped perimeter that may have destroyed buildings. We determined whether each building was a) destroyed by the wildfire and never rebuilt, b) destroyed by the wildfire and rebuilt (noting the image year of rebuilding), c) survived the wildfire, or d) newly built after the wildfire (noting the image year that the new construction appeared). We defined rebuilding as another building appearing in the same location, but we did not have information on building type or owner (e.g., a home replaced by a commercial building would count as "rebuilt" in this work). Ultimately, 11 fires had sufficient data over time and sufficient building loss (at least 20 buildings destroyed). The 11 wildfires were located in both Northern and Southern California, spanning multiple ecological and socioeconomic zones (see Appendix D for detailed descriptions of each of these wildfires). For data after 2000, we used a national pre-existing data set, and selected those with sufficient building loss and temporal imagery (n=17) / (Alexandre et al. 2015, Kramer et al. 2018). Combined we had data on 28 fires that occurred between 1970 and 2013.

We then generated summary statistics for the number of buildings destroyed, rebuilt, and newly constructed within fire perimeters, over time, differentiating between short-term (3-6 years post fire) and long-term (13-25 years post fire). We calculated the rebuilding rates and growth rates due to new construction for each wildfire.

$$Rebuilding\ rate = \frac{Total\ rebuilt\ buildings}{\text{Total destroyed buildings}}\ x\ 100$$

$$Growth\ rate = 100\ x\ \frac{\text{new buildings} + \text{buildings that survived}}{\text{buildings that survived}} - 100$$

Objective C) Analyze wildfire risk for post-fire development

Our next objective was to use this data on rebuilding and new development (Obj. B) to analyze the wildfire exposure of new and rebuilt buildings. The spatial placement and arrangement of buildings can play a strong role in the probability that a building will be destroyed if a wildfire occurs (Syphard et al. 2012, Alexandre et al. 2016), requiring us to look at building-level risk and investigate how rebuilding and new construction alter wildfire exposure. To identify whether rebuilding and new construction took place in locations with higher risk, and if this changed over time, we constructed risk models for each of the 28 wildfires in the dataset, and calculated risk using a probit specification (Wooldridge 2011, StataCorp 2017). The probit model is well-suited for cases where the dependent variable can take on only two values (i.e., rebuilt or not rebuilt; destroyed or not destroyed). The unit of analysis was the individual building, and the dependent variable was equal to one if a building was destroyed and zero if not. We parameterized the probit model using a host of variables that have been found to influence wildfire risk to buildings in other settings including: land cover, elevation, topographic position index, slope, distance to public land, distance to metropolitan areas, distance to wildfire perimeter, and the number of buildings within 100 meters at the time of the wildfire. The output of the probit model was the predicted probability of a building being destroyed by wildfire, given its set of covariates (StataCorp 2017). For more detail on probit models please see Kramer et al. (in prep).

Using these wildfire risk models, we predicted, for each building in each wildfire, the probability that the building would be destroyed. We then compared, for each wildfire, the predicted wildfire destruction probability of buildings that were rebuilt versus those that were destroyed but not rebuilt, applied a two-sample t-test to identify significant differences in the mean wildfire risk between rebuilt and not rebuilt buildings in each wildfire, and counted the number of wildfires where there were significant differences. Analyses therefore identified if, on average, buildings that were rebuilt were in higher or lower risk locations than those that were destroyed but not rebuilt.

Using the same models, we then compared wildfire exposure for new construction to buildings present at the time of the fire. We first focused on short-term construction (3-6 years post-fire) (n=17 fires with sufficient data). To compare wildfire exposure we applied the coefficients from each wildfire's risk model to make out-of-sample predictions for newly constructed buildings. We then compared the predicted risk for new construction to the wildfire risk of all buildings present at the time of the wildfire. Once again, we applied a two sample t-test to test for statistically significant differences, counted the number of wildfires with significant differences, as well as the average difference in means for significant observations. Analyses therefore identified if, on average, new construction was in higher or lower risk locations than buildings that existed before the fire.

We then investigated how building patterns changed over the full time frame (up to 25 years), for rebuilding and new construction (n=11 fires with sufficient data). We regressed predicted risk for rebuilt buildings on the number of years that passed between the building being destroyed and rebuilt. We conducted this linear regression for each wildfire individually. The components of the model were the number of years between a wildfire destroying the building and when that building was rebuilt (as the dependent variable), the predicted wildfire destruction probability (as the independent variable), and an intercept term. A positive and statistically significant coefficient indicated that buildings with lower wildfire risk were rebuilt more quickly than buildings with high risk. A negative and statistically significant coefficient indicated that buildings with high wildfire risk were rebuilt before buildings with lower wildfire risk. We conducted an analogous analysis for new construction to test whether buildings built soon after a wildfire had higher or lower probability of wildfire risk than those built longer after it. For more detail on methods and robustness checks please see Kramer et al. (in prep).

Objective D) Analyze spatial patterns of wildfire losses relative to policy and outreach. Our final objective was to examine the spatial patterns of wildfires loss, and how these losses related to higher-level (national, state) policy and outreach programs. These national and state-level analyses allowed us to examine policies more broadly than case study research in Objective A. We conducted these studies using digitized data on buildings before and after wildfires to determine how wildfire losses were distributed in relation to WUI designation, outreach programs, and California's Fire Hazard Severity Zones (Kramer et al. 2018, Kramer et al. 2019).

For our national study, we used a pre-existing dataset of building locations and outcomes within fire perimeters (threatened and destroyed) from 2000 to 2013 (Alexandre 2015, Kramer et al. 2018). We compiled data on WUI maps and fire education and mitigation outreach programs ('national fire outreach programs', including Fire Learning Network landscapes, Fire Adapted Communities, and Firewise Communities) (Kramer et al. 2018). We first determined the proportion of buildings threatened and destroyed by wildfire within the WUI, using a national WUI map based on definitions from the federal register (USDA and USDI 2001, Radeloff et al. 2018). For all buildings outside the WUI we calculated average distance to the WUI. For buildings that were destroyed outside the WUI, we examined the housing density and wildland vegetation density in their census block and compared them to the WUI definitions values for housing and vegetation (USDA and USDI 2001, Radeloff et al. 2018). We also examined whether buildings were destroyed in intermix (housing intermingled with wildland vegetation) or interface (housing without substantial wildland vegetation but in close proximity to wildland vegetation).

To determine the relationship between buildings and fire outreach at the scale of wildfires, we calculated the number of buildings threatened and destroyed within each fire perimeter, and the average distance from these to the nearest national fire outreach program. Finally, Firewise programs were the most prevalent among the national fire outreach programs, and the only program for which we had dates of establishment. We therefore compared the date of establishment of each Firewise community to the date that nearby buildings were threatened or destroyed by fire, to determine if Firewise programs were established before or after wildfire events that threatened homes. For more on data and analyses, please see Kramer et al. (2018).

We then expanded upon these analyses using a longer time frame to examine wildfire losses and policy for the state of California (Kramer et al. 2019). We used historical data generated in Objective B, combined with pre-existing data sets (Alexandre 2015, Kramer et al. 2018), to examine building loss to wildfire over a 28-year period (1985–2013) in relation to WUI maps and Fire Hazard Severity Zones (FHSZs) (we chose 1985 as a date close in time to WUI and FHSZ mapping). FHSZ maps are generated by California state government, and dictate wildfire mitigation standards, based on factors such as fuel, slope, and wildfire weather. We examined the rates of building loss and overall wildfire destructiveness (total number of buildings destroyed), by WUI designation (intermix, interface), non-WUI designation (urban, rural), and FHSZs. Finally, we also included the 2017 Tubbs fire as a recent case study of a notably destructive and urban wildfire in order to fully characterize the challenges wildfire poses to homes and buildings in this densely developed and fire-prone state. For more on data and analyses, please see Kramer et al. (2019).

Results and Discussion

Objective A-Community-level policy change and adaptation after wildfire.
In each of our study sites, local government and community leaders were revising wildfire mitigation practices post-fire, most commonly through enhancing suppression and emergency response (Table 2) (Mockrin et al. 2018). Our findings concur with other studies demonstrating that such improvements in suppression are a common tactic in response to wildfire threats, and garner community support (Jakes and Sturtevant 2013, McCaffrey et al. 2013). However, other responses were also present at our sites, including additional investment in planning (e.g., creating or revising a community wildfire protection plan), an increased number of Firewise communities, and enhanced community education and outreach campaigns (e.g., encouraging vegetation mitigation on private properties) (Table 2).

We concluded that these changes related to a site's previous experience with destructive wildfire, and past investment in formal wildfire management and regulation. Sites with the most change after wildfire—particularly in education, outreach, and planning documents—were all locations with moderate to high levels of previous investment in wildfire-related land use planning, and places where destructive wildfire was novel. These locations had the capacity and staff resources to respond to wildfire at the community level following an incident. These findings agree with other wildfire and hazards studies that demonstrate the importance of local government capacity, external resources, and issue champions (Michaels et al. 2006, Prokopy et al. 2014, Labossière and McGee 2017). However, the changes we saw were not uniform across settings—that is, not all locations with similar characteristics and fire histories pursued the same changes. Other factors, including social capital, histories of land use development, local culture, partnerships and collaborations, relationships between and among jurisdictions, among others, also influenced the paths that locations took post fire.

Across our study sites, however, local governments largely declined to take action via land use regulations or building standards (these tools were also rarely used before the focal fires) (Table 2) (Mockrin et al. 2018). Although Duerksen et al. (2011) found that such regulations were often enacted after a wildfire event, we concur with others who found that regulations are not readily implemented or updated (Muller and Schulte 2011, McCaffrey et al. 2013, Mockrin et al. 2016). In our study, both locations that had such regulations (Caughlin Ranch NV and Station CA) gained them in response to a previous wildfire that prompted state-level action (2009's Angora Fire in Nevada, 1991's Tunnel Fire in California) (Plevel 1997, Nevada Division of Forestry 2010). States may also decline to pursue such actions, even after notable wildfires (e.g., Colorado considered but did not pursue such standards after a series of record setting fires in 2010-2013) (Mockrin et al. 2016).

Further analysis of our interviews with local government revealed that while land use was rarely used to restrict or shape development, community leaders in multiple sites had considered such tools (Mockrin et al. 2020). Across our diverse study sites, we found six common challenges to using these tools, many internal to local government and communities: government staff perceptions of wildfire risk, staff opinions of planning and regulations, policy coordination challenges, other governmental priorities, and a lack of public support for land use planning and regulations to reduce wildfire risk). These themes are not mutually exclusive, and were often interrelated.

Some of these concerns were readily linked to site characteristics. For example, in nonmetro or rural sites many respondents shared similar concerns about local government capacity, questioned the efficacy of/need for land use efforts, felt a need to encourage housing development to further local economic growth, were concerned about broader social needs of residents, and faced a lack of public acceptance for land use planning. In contrast, sites with more investment in land use regulation and planning (typically metro sites) grappled with policy coordination challenges, within and across jurisdictions. However, many of our sites had similar concerns, despite their different settings. In particular, public resistance to using land use planning to reduce wildfire risk was evident even in metro areas, formalized developments, and amenity destinations, settings where previous studies suggested residents accepted land use regulation (Paveglio et al. 2015, Paveglio et al. 2018). Our findings agree with other emerging research (Edgeley et al. 2020) that the scale and scope of local government, the diversity of residents and development, and the social fit between policies and local settings are all critical to consider when using land use planning and regulations to reduce wildfire risk.

Table 2. Community level wildfire mitigation, including vegetation treatment, education, Firewise programs, and wildfire-related planning and regulations, before and after wildfire. For each category any changes after the study fire are noted with a +sign and in bold.

Name	Is fire novel?	Previous land use plan/regs	Ed/outreach	Firewise	Burn bans	Building code	Home mitigation regulations	CWPP[a]	Other changes
Caughlin Ranch NV	Novel	Mod	Available	None	Yes	Yes	Yes[b] **+IWUI county only**		**+Revise HMP**
Hwy 31 SC	Novel	Mod	Limited **+Expanded**	2-4 **+20**	Yes **+city/county**	Yes	**+Overlay N. Myrtle Beach**		**+ Revise HMP and Comprehensive Plan**
Loco-Healdton OK	No	Low	Limited	None	Yes				
Monastery WA	Novel	Mod	Limited **+Expanded**	1[c] **+1**[c]	Yes	Yes			
Monument AZ	Novel	Mod	Limited **+Expanded**	None **+1**[c]	Yes	Yes (county, 1 fire dept) **+1 more fire dept.**		**+New CWPP**	**+ Revise HMP**
Possum Kingdom TX	Novel	Low	Limited	None **+1**[c]	Yes				**+Revise Emerg Ops Plan**
Station CA	No	High	Available	None	Yes	Yes	Yes[e]	Fire Plan[d]	**+ Revise HMP**
Wallow AZ	No	High	Limited **+Expanded**	None **+1**[c]	Yes	Yes		Yes **+Revise CWPP**	**+ Revise HMP**

[a]Caughlin Ranch NV and Monastery WA had older assessment documents or CWPPs, but not current ones. LA has county-wide fire plan similar to a CWPP
[b]Present in both city and county in limited areas
[c]In close proximity to fire, not necessarily within fire perimeter
[d]As required by the state of CA

Objective B) Map rebuilding and new construction after historical wildfire events

In total, we found 7,075 buildings destroyed by 28 wildfires, which was 2% of all buildings within those fire perimeters (Table 3). Over half of those destroyed buildings (58%) were rebuilt within 3-6 years (Table 3), similar to a prior study that found a short-term rebuild rate of 41-75% in California (Alexandre et al., 2015). Long-term, nearly all buildings were rebuilt within 13-25 years (94% of 2,985, Table 3). Our study was the first to examine long-term rates of rebuilding statewide, and these findings agree with the available information on long-term trends after the 1991 Oakland Hills (Tunnel) Fire (Simon 2014, Eriksen and Simon 2017). Across California, with only 6% of destroyed buildings not rebuilt after 13 to 25 years, destructive wildfire resulted in few buildings being permanently removed from the landscape. These rebuilding trends are consistent with research on wildfire (Mockrin et al. 2015, Mockrin et al. 2016) and other disasters (Solecki and Michaels 1994b, Birkland 2006) demonstrating that the built environment tends to be restored after disaster.

Rebuilding rates at the individual wildfire level were variable, however, ranging from 13% to 100% rebuilding 13-25 years post-fire (Table 3, Figure 2). Similarly, a short-term study of rebuilding post-fire found high variability in individual wildfire outcomes (Alexandre et al. 2015). The same national study also found that new construction was variable in the short-term post-fire (Alexandre et al. 2015). In contrast, we found consistently high new building rates over time for our wildfires in California, with only two exceptions, the 1991 Oakland Hills and 1985 Baldwin Hills Fires, where already dense development prior to the wildfire meant that there was little undeveloped land available for new construction (Figure 3, Appendix D). For other fires, new construction rates were as high as 205%, and cumulative totals of buildings over time within a fire perimeter clearly demonstrate that new construction—not rebuilding—was the primary force shaping development patterns post-fire long term (Figure 3).

Table 3. Rebuilding and new construction totals and proportions over short (3-6 year) and long-term (13- 25 years)

		3-6 years post-fire (28 wildfires; 1970-2009)	13-25 years post-fire (11 wildfires; 1970-1999)
All buildings	Total survived	50,463	27,823
	Total destroyed	7,075	2,985
	Total rebuilt	4,120	2,793
	Proportion rebuilt (%)	58	94
	Total new construction	7,760	23,404
	Growth from new (%)	15	84
Range of values by wildfire	Proportion rebuilt (%)	1 - 99	14 – 100
	Growth from new (%)	0 - 85	2 - 205

Figure 2. Boxplots of distribution of values among fires for a) building destruction, short-term rebuilding rate, and long-term rebuilding rate and b) new construction rates, short- and long-term

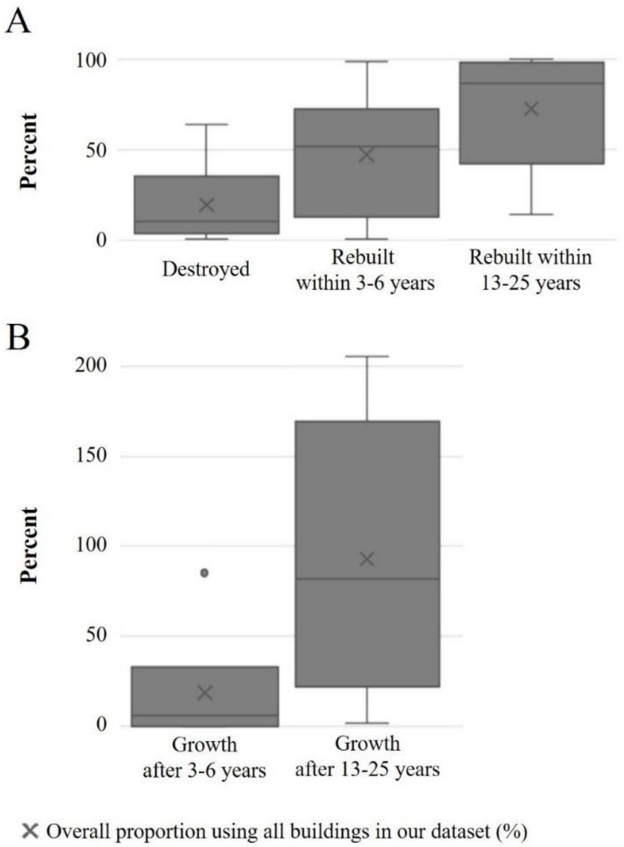
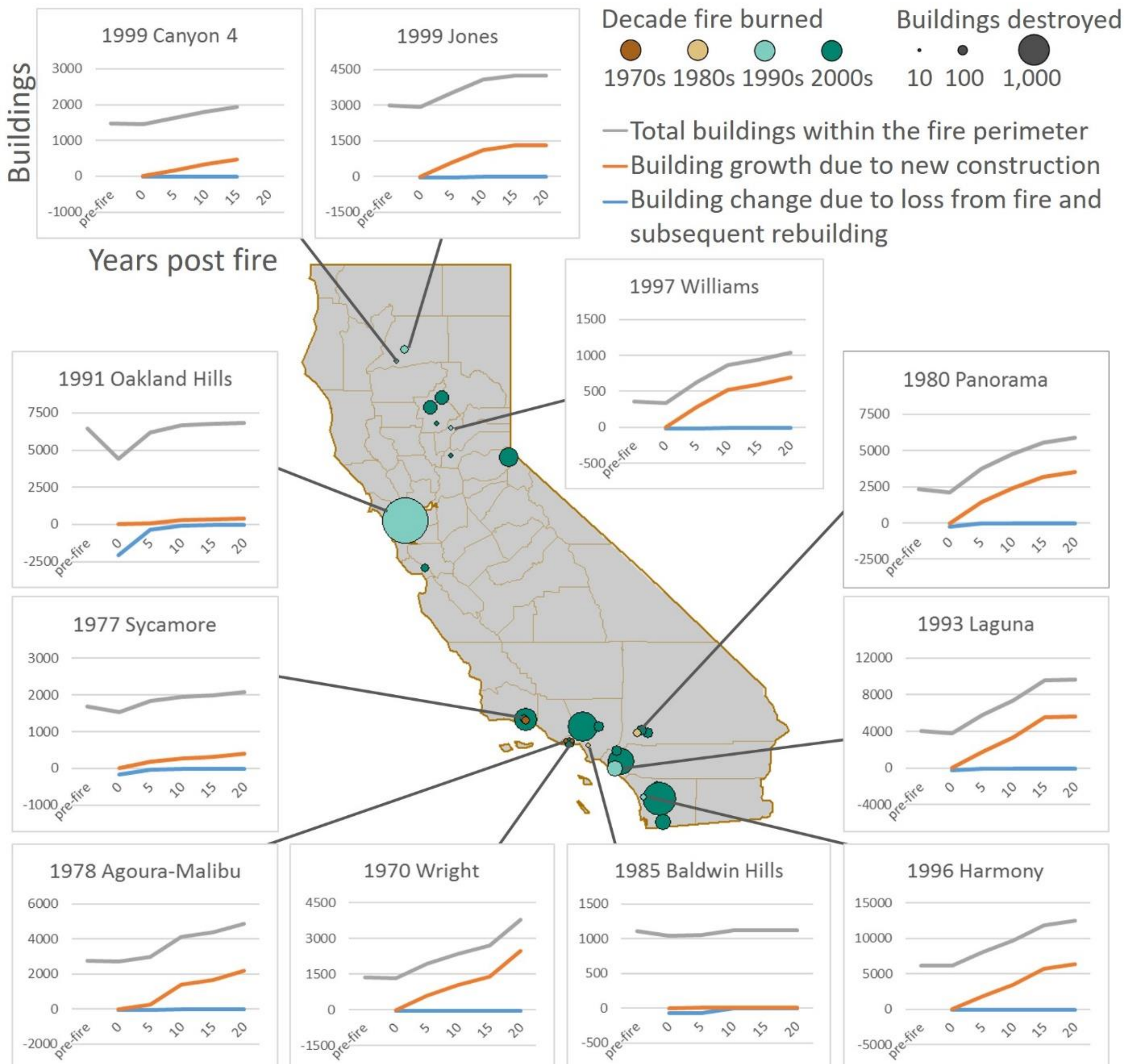


Figure 3. Trends in rebuilding, new construction, and overall buildings within the perimeters of 11 California wildfires from pre-fire to 13 to 25 years after the wildfire burned. Note that building loss due to wildfire is reflected by a negative trajectory



Objective C) Analyze wildfire risk for post-fire development

We then used our data on development over time in California to examine how building-specific wildfire risk was changing with rebuilding and new construction. We found no consistent trend of reduced risk of wildfire loss for either rebuilt or newly constructed buildings in the short term (3-6 years), concluding that we saw minimal evidence for adaptation. Rebuilt buildings were in significantly lower risk locations in six out of 28 wildfires, but in higher risk locations in five wildfires (Figure 4, Table 4, Table 5), with no significant difference in the remaining 17 wildfires (Figure 4, Table 5). The plentiful new construction after a wildfire also showed no consistent trends toward lower-risk locations. Of the 17 wildfires where new construction occurred within three to six years of the wildfire, new buildings were located in significantly lower risk areas in eight wildfires, but significantly higher risk areas in four wildfires (Figure 4, Table 4, Table 5), and for the remaining five wildfires, there was no statistically significant difference (Figure 4, Table 5). In other words, neither rebuilding nor new construction indicated consistent adaptation to wildfire in the form of better building placement in the short-term.

Long-term trends (13-25 years after fire) were similar: those buildings that were rebuilt were not located in lower risk locations, and new construction often occurred in higher risk areas. Of nine fires for which we had long-term data, the location of rebuilt buildings became higher risk over time in a single wildfire, and the opposite was true for two wildfires (Figure 4, Table 5, Table 6). The remaining six wildfires showed no significant difference between the building location and the timing of rebuilding (Figure 4; Table 5, Table 6). For new construction, four wildfires showed increasing risk over time for building locations, while the remaining five wildfires showed no significant trend (Figure 4; Table 5, Table 6).

We were surprised to find that new construction did not occur in lower risk areas, as we expected new construction to be adaptive, simply because new construction affords more flexibility in location compared to rebuilding. Although more wildfires showed significant reductions in wildfire risk for new construction than for rebuilding, such post-fire adaptation was still uncommon, occurring in less than half of the fires examined. Wildfire risk for new buildings also increased as time passed, indicating that lessons learned from wildfires may fade over time. The lack of adaption we found in building placement is consistent with other disasters (Solecki and Michaels 1994, Birkland 2006), which also did not show major changes in building pattern; and with studies showing that the average wildfire risk of developed parcels has increased over time, as preferences for high elevation and forested settings emerged (Platt et al. 2011). However, we lack data on other forms of adaptation at the building- (building materials or landscaping) or community-level (fuel treatments, suppression capabilities), which also affect wildfire risk.

Figure 4. Map of significant trends of risk for a) rebuild and b) new building locations, 3-6 years after fire, as well as c) rebuild and d) new building locations, over time (comparing risk of building 13-25 years post-fire to 3-6 years post-fire

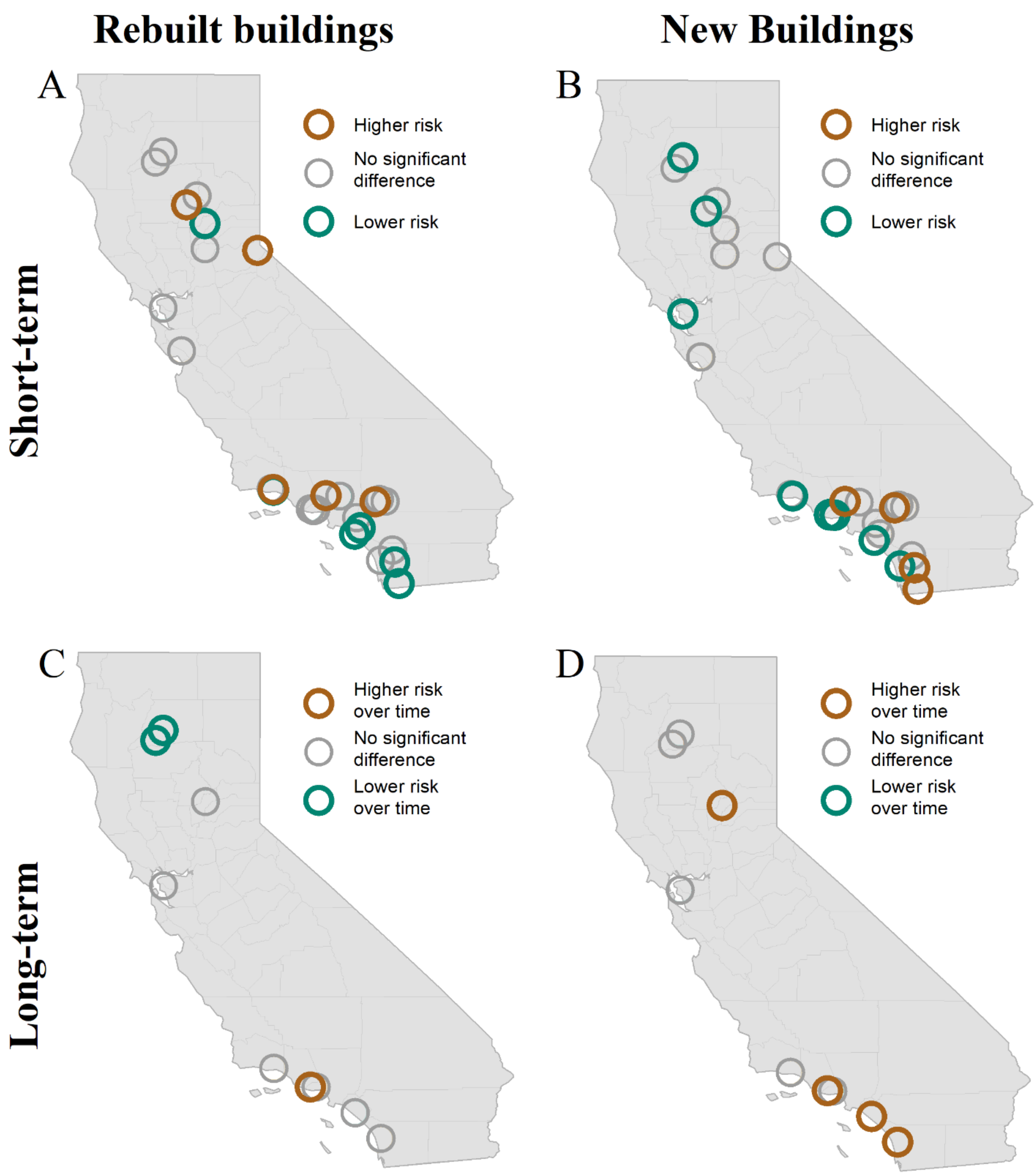


Table 4**.** Statistical output of probit modeling, short-term (3-6 years). Bold indicates significance at 95% confidence

		P(fire destruction) in rebuilt buildings lower than those not rebuilt			New build has lower P(fire destruction) than pre-fire		
			95% confidence			95% confidence	
Year	Fire Name	coeff.	low	high	coeff.	low	high
2007	Angora	**-0.071**	-0.125	-0.016			
1978	Agoura-Malibu	0.003	-0.052	0.057	**0.023**	0.03	0.02
2008	BTU Lightning Complex	-0.005	-0.058	0.048			
1985	Baldwin Hills	N/A (risk perfectly predicted, so no predictions can be made)					
2007	Corral	-0.008	-0.080	0.064	0.006	0.085	-0.072
1999	Canyon 4	-0.013	-0.038	0.012	0.003	0.005	0.000
2008	Freeway Complex	0.015	-0.020	0.050			
2008	Gladding	0.204	-0.070	0.478			
2007	Grass Valley	-0.071	-0.175	0.032			
2007	Harris	**0.105**	0.050	0.161	**-0.048**	-0.020	-0.076
2008	Humboldt	**-0.125**	-0.172	-0.079	**0.094**	0.167	0.021
1996	Harmony Fire	0.010	-0.036	0.057	**0.004**	0.004	0.003
2009	Jesusita	-0.040	-0.107	0.028	0.030	0.138	-0.078
1999	Jones	0.017	-0.010	0.045	**0.011**	0.013	0.009
1993	Laguna	**0.189**	0.108	0.270	**0.075**	0.083	0.067
2007	Poomacha	0.031	-0.018	0.080	0.002	0.035	-0.032
1980	Panorama	**-0.230**	-0.348	-0.112	**-0.099**	-0.095	-0.104
2007	Santiago	**0.907**	0.751	1.063			
2008	Sayre	**-0.073**	-0.106	-0.039	**-0.540**	-0.394	-0.686
2007	Slide	0.022	-0.028	0.071			
2009	Station	0.236	-0.002	0.473			
2008	Summit	-0.082	-0.229	0.065			
1977	Sycamore	**0.204**	0.026	0.382	**0.072**	0.090	0.053
2008	Tea	**-0.067**	-0.122	-0.013			
1991	Tunnel/Oakland Hills	0.050	-0.038	0.139	**0.122**	0.152	0.092
2007	Witch	**0.037**	0.024	0.050	**-0.014**	-0.007	-0.020
1997	Williams	**0.244**	0.050	0.439	0.000	0.014	-0.015
1970	Wright	0.042	-0.050	0.133	**0.028**	0.030	0.025

Table 5: Counts of wildfires with significant differences between building location (new and rebuilt) and wildfire risk over short (3-6 year) and long-term (13- 25 year)

	Short-term rebuilding *p(fire destruction) in rebuilt buildings lower than those not rebuilt*		Short-term new construction *p(fire destruction) of new construction lower for pre-fire*		Long-term rebuilding *p(fire destruction) of rebuilt buildings higher over time*		Long-term new construction *p(fire destruction) of new construction higher over time*	
	# fires	Mean difference	# fires	Mean difference	# fires	Mean difference	# fires	Mean difference
Significantly Positive	6	0.281	8	0.053	1	33.780	4	12.476
Significantly Negative	5	-0.113	4	-0.175	2	-82.955	0	-----
No Effect	17	-----	5	-----	6	-----	5	-----

Table 6: Statistical output of probit modeling 13 to 25 years after fire. Bold indicates significance at 95% confidence

	Rebuilds longer after fire have higher probability of destruction			New construction longer after fire have higher probability of destruction		
	P(fire destruction)	95% confidence		P(fire destruction)	95% confidence	
Fire Name		low	high		low	high
Agoura-Malibu	**33.78**	10.89	56.67	**6.661**	2.07	11.26
Canyon 4	**-128.2**	-208.64	-47.76	-14.76	-34.02	4.50
Harmony Fire	-11.82	-28.22	4.58	**27.57**	21.50	33.64
Jones	**-37.71**	-65.52	-9.90	0.276	-4.86	5.41
Laguna	0.489	-0.06	1.04	**8.345**	7.64	9.05
Sycamore	-1.426	-3.76	0.90	-0.276	-0.85	0.29
Tunnel/Oakland Hills	0.319	-0.14	0.78	1.204	-0.15	2.56
Williams	16.4	-6.38	39.18	**7.33**	0.18	14.48
Wright	-24.32	-153.48	104.84	2.986	-4.55	10.52

Objective D) Analyze spatial patterns of wildfire losses relative to policy and outreach
Our final objective was to examine how wildfire losses were distributed in relation to national- and state-level policies and wildfire outreach. Nationally, only a very small portion of the WUI (less than 1%) burned between 2000-2013, but WUI was a focal area for buildings threatened and destroyed by wildfire, and an area of high rates of loss (Kramer et al. 2018). Most buildings threatened by fire were in the WUI (59%). Of the 41% of threatened buildings not in the WUI, most were close to it (1.60 km and 2.07 km on average for destroyed and surviving buildings respectively. Buildings that were destroyed were more often located in the WUI than buildings that survived wildfire (69 v. 58% respectively), and intermix (n=7,280) losses were higher than interface (n=4,566) (Kramer et al. 2018). For the 31% of destroyed buildings that were outside the WUI, low housing density was almost always the reason for non-WUI designation (93% were below the WUI housing threshold, and substantially so—on average less than 1 housing unit/km^2). We note that the Federal Register definition does not consider risk explicitly, and sizeable WUI areas, especially in the north-eastern US, have low risk of wildfire. In general, however, the current relationship between wildfire exposure and losses and WUI maps is a validation of the existing national level maps and WUI definition from the Federal Register (USDA and USDI 2001, Radeloff et al. 2018).

National wildfire outreach programs were generally close to both recent fire perimeters and buildings threatened by fire. Most national fire outreach programs (89%) were within 50 km of a fire, and 51% of buildings destroyed by wildfire were within 25 km of a national fire outreach program respectively) (Kramer et al. 2018). Although 17% of buildings destroyed by wildfire were 50 km or more from the nearest national fire outreach program the total number of buildings threatened or destroyed by these wildfires was low (Kramer et al. 2018).

We had data on the timing of outreach program establishment only for Firewise communities. Firewise community establishment occurred often after a fire had burned buildings, not before (Kramer et al. 2018). The majority (76%) of destroyed buildings were located closest to a Firewise community that was established after that building was destroyed. However, when we considered only threatened buildings we found that 31% of Firewise communities were established after the majority of nearby buildings were threatened and 69% of Firewise communities were established before buildings were lost to wildfire. Our results in Objective A similarly found that three of our study sites expanded Firewise activity post-fire. We note however that this national data set started in 2000, and communities may have had wildfire experience prior.

California was by far the state with the greatest number of wildfire losses (60% of all destroyed buildings nationally). Accordingly, we expanded these analyses, using a longer time frame to examine wildfire losses and policy in greater detail for the state of California (Kramer et al. 2019). From 1985 to 2013, we had 8,722 buildings destroyed by wildfire in 89 fires, for an overall destruction rate of 14%. Although only 32% of buildings in California are located in the WUI, 82% of the destroyed buildings were located in the WUI, a higher proportion of WUI losses found nationally (Kramer et al. 2018). We found that the interface WUI, i.e. settled areas with little wildland vegetation that are near large blocks of wildland vegetation, is where the greatest total amount of building destruction occurred in California. Interface WUI accounted for 50% of all buildings destroyed in wildfire, despite covering only 1.8% of the total area burned and comprising only 27% of buildings in California (Table 7). Within fire perimeters, buildings in the interface WUI had the highest chance of destruction from wildfire (15.6%, in comparison to 11.3, 11.6 and 14.1 for urban, intermix, and rural areas respectively). This may have been due to non-wildland fuel in these areas (e.g. homes, vehicles, propane tanks and landscaping vegetation) or fires moving from home to home in more dense housing areas, though analyses of distance between destroyed and surviving buildings suggested that building density was unrelated to destruction rates. Fire Hazard Severity Zones accurately matched area burned and destruction rate for data from 1985-2013. Of all area burned by destructive wildfires in our sample, 86% fell into the Very High hazard class and captured 78% of destruction. Destruction rates were highest for High and Very High classes (13% in both; see Part 3 in Supplementary material) (Kramer et al. 2019).

We also examined the Tubbs fire, which was at the time a notably destructive and recent wildfire. We found that for the Tubbs fire, similar to other California wildfires, destruction was primarily in the WUI (71 and 82% destruction respectively; Table 7). However, the Tubbs fire had approximately equal destruction in the interface and intermix WUI (35 and 36% respectively) (Table 7). The Tubbs was unique in that 1/4th of destruction in the Tubbs fire occurred in urban areas, compared with 4% for California fires (Table 2). Indeed, only 5 fires in our dataset of 89 had any destruction at all in urban areas, totaling 349 buildings, compared with 1,430 urban buildings destroyed in the Tubbs fire alone (Kramer et al. 2019). Other recent and highly destructive fires including the 2018 Carr, Camp, and Woolsey fires included no urban area within their perimeters, exemplifying the rarity of building destruction by wildfire in urban areas. The destruction rate was also very high in the Tubbs fire across urban areas, as well as interface and intermix WUI (Table 7). The Tubbs fire also departed from the usual patterns observed for Fire Hazard Severity Zones, with fewer losses in the highest rated areas. The Tubbs fire burned the most area (51%) in Moderate zones and the most buildings (39%) in Urban (unrated) areas, where destruction rate was also the highest (73%; see more in Kramer *et al.* (2019)).

Table 7: California wildfire losses relative to WUI classes (1985-2013), as well as the 2017 Tubbs fire

	All California *(n=89)*	Tubbs *(n=1)*
Area (%)		
Non-WUI, urban	0.1	1.3
Interface WUI	1.8	5.2
Intermix WUI	9.5	41.2
Non-WUI rural	88.6	52.3
Proportion total destruction (%)		
Non-WUI, urban	4.0	25.4
Interface WUI	50.1	34.9
Intermix WUI	32.0	35.7
Non-WUI rural	13.9	4.0
Destruction rate (%)		
Non-WUI, urban	11.3	75.7
Interface WUI	15.6	72.4
Intermix WUI	11.6	61.5
Non-WUI rural	14.1	35.2

Science delivery

We shared our results with managers, planners, and others who study wildfire social science and hazards recovery through presentations, webinars, and academic publications (Appendix B). We presented research findings from this effort through two Fire Science Consortia, the Southwest Fire Science Consortium and the California Fire Science Consortium, as well as two scientific conferences, the Association of American Geographers and the Association of Fire Ecology annual meetings. Mockrin (co-PI) also shared results at a Cohesive Wildland Fire Management Strategy Workshop, which reaches managers and scientists from federal, state, and local government, as well as academics and insurance industry professionals. We gave invited presentations to the Personal Insurance Federation of California and American Planning Association (DC office and annual meeting). Our findings from Objective D in California were shared as by Forest Service R&D communications staff via press release, newsletter, and infographic (Appendix B). Finally, we published our academic articles in journals with broad readership, shared articles on local policy change (Objective A) with the interviewees who provided information, and ensured that academic articles were posted for free public distribution on Forest Service websites.

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

Our overarching goal was to examine if, and how, destructive wildfire changes the wildland urban interface through building patterns and community-level adaptation. The highly dispersed and variable nature of WUI communities, in addition to the locally-driven character of post-fire responses means that it is challenging to understand wildfire impacts and outcomes. Accordingly, our original objectives were designed to examine this issue from multiple spatial and temporal scales, using social and biophysical data. We completed our original objectives, and added a fourth one (Objective D) when we realized that a deeper understanding of wildfire losses would strengthen our evaluation of post-fire outcomes.

Examining wildfire losses nationally, we found that wildfires typically destroy buildings within the WUI (primarily intermix), and in locations in proximity to national wildfire outreach programs such as Firewise (Kramer et al. 2018). Although the majority of losses occurred within WUI areas nationally—and for California—we found other notable trends: Interface areas contained half of the losses in California, very low density (rural) areas contained more than 25% percent of losses nationally, and one thus far unique wildfire, the 2017 Tubbs wildfire in California, had a record number of losses in an urban area.

Once a destructive wildfire occurs, communities can chose a variety of paths forward, with opportunities to reduce potential future wildfire losses through changes to the built environment, or investment in planning, education, and/or suppression, among other options. Our case study research revealed that even after destructive fire, many communities prefer to pursue efforts that will easily gain public support, including enhancing suppression, education, outreach, and hazard planning (Mockrin et al. 2018). We found support for these investments nationally as well: wildfire losses spur communities to establish Firewise communities (Kramer et al. 2018). Destructive wildfire is therefore an opportunity to pursue wildfire mitigation goals at the community level, particularly for sites where destructive wildfire is novel and there is local government capacity to capitalize on this occasion (Mockrin et al. 2018).

However, local governments in our study sites largely declined to pursue land use planning to restrict or otherwise guide development after a destructive wildfire (Mockrin et al. 2018). Evidence from California wildfires (1970-2013) suggests fires lead to more built infrastructure, without consistently reducing exposure: few buildings were permanently removed from the landscape, new development was substantial, and neither rebuilding nor new construction indicated consistent adaptation through better building placement, short- or long-term. In fact, long-term, approximately half of the wildfires showed increases in building-level risk over time with new development (n=4 fires), while the other fires showed no significant change (n=5). Although these data are necessarily incomplete—we lack detailed information on all parcels available to be developed, economic markets over time, or building- and community-level mitigation pursued—they reveal no obvious trends of adaptation post-fire in California from 1970 onwards (it remains to be seen if the 2017 and 2018 wildfires losses in northern California will have similar policy and development outcomes; these fires caused magnitudes more housing loss than study fires).

Implications for management and policy

In the United States, where housing development overwhelmingly drives WUI growth (Radeloff et al. 2018), which in turn increases wildfire risk (Syphard et al. 2007, Syphard et al. 2017), it is notable that wildfire experience does not appear to check growth or substantially shape development. However, our case study work also revealed that wildfire experience did lead to enhance suppression, education, and outreach, primarily in communities where destructive wildfire was novel and there was at least moderate government capacity to pursue such initiatives. These efforts are likely to meet with public approval, and also require less technical expertise and policy coordination than retrofitting infrastructure or revising land use planning.

Our findings raise questions about the pathway to FAC for places where housing is already extensively developed, destructive wildfire is commonplace, and/or interest in adaptation and capacity for using formal tools and actions is low. Successful examples of community wildfire risk reduction post-fire, including land use planning, in a range of settings, will be increasingly valuable. This research suggests several areas where additional resources may be helpful, including disseminating information on wildfire risks to local government and elected officials, and providing examples of effective plans, regulations, and policy coordination. Such support and broadening of the model of FAC could be of particular benefit in rural areas that have minimal resources and where unmet human and social needs compete with hazard preparation for scarce resources. Some of these locations are unlikely to develop further, but for those that do, proactively building local support for and awareness of wildfire mitigation can help avoid the challenge of reconfiguring existing neighborhoods and harmonizing existing and new policies. Finally, the iterative adaptation thought to occur with experience, a central tenet of, the FAC concept, will benefit from further explication. Local government and community leaders may become inured to frequent wildfires, and for those places that have already made considerable investment in formal wildfire mitigation, it is unclear what next steps, if any, they want to pursue.

The nature of these challenges in managing and minimizing wildfire loss across diverse and widely scattered communities also highlights the value of spatially explicit data on wildfire losses and recovery over time. We devoted considerable resources to building a data set for historical losses. However, there is no national effort to map wildfire losses, or follow recovery over time, despite the growing scope and scale of wildfire losses and the value of assessing management and policy outcomes. For example, we used these data to examine spatial distribution of wildfire losses and were able to confirm that wildfire losses are occurring primarily within and in close proximity to WUI, as defined in the Federal Register and mapped by the SILVIS group (USDA and USDI 2001, Radeloff et al. 2018). This finding demonstrates that the WUI environment as currently defined is an appropriate focal point for managers and policy makers, while also suggesting ways in which it could be enhanced (see below).

Considerations for future research

This effort generated valuable knowledge about wildfire rebuilding and recovery over time, including our first information on historical trends. However, knowledge about wildfire impacts and outcomes remains incomplete. Remaining research questions to consider include:

1. Re-examining WUI definitions and maps

While most wildfire losses occur in or in proximity to the WUI, the WUI is vast and risk from wildfire varies. Wildfire risk data and additional information on building locations would enhance WUI maps and our understanding of wildfire losses, potentially providing future insight into some of the state-level and local variation we found (for example, record losses in WUI interface in California). The existing WUI definition from the Federal Register (USDA and USDI 2001, Radeloff et al. 2018) is from two decades ago and there are increasing opportunities to re-examine the distribution and variation of wildfire losses.

2. Determining sources of variation in rebuilding outcomes

We found no consistent trend of reduced risk of wildfire loss for either rebuilt or newly constructed buildings after wildfire, but responses for individual wildfires were variable. For example, over the short-term, locations for rebuilt buildings were lower risk in 6 out of 28 wildfires, and locations for new construction were at lower risk in 8 out of 17 wildfires. It is not clear why these different outcomes in rebuilding rates and adaptation in placement of buildings emerged. Decisions to rebuild and develop are complex, resulting from multiple factors (insurance availability, future wildfire risk, housing markets, land use policies, and building use (primary home, commercial building, vacation home).

3. Examinging adaptation by multiple actors and scales

Buildings, individual residents, and local government community leaders can all influence future vulnerability to wildfire. This study examined data on building placement and community-level mitigation, but a fuller picture of wildfire adaptation could integrate other building- and individual-level risk mitigation actions. Such links would be helpful in assessing policy and program efficacy, and providing a path towards wildfire risk reduction.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products.

1. Articles in peer-reviewed journals (specify whether in press, accepted for publication, in review [submitted for publication], or planned/in preparation).

Kramer, H. A., M. H. Mockrin, P. M. Alexandre, S. I. Stewart, and V. C. Radeloff. 2018. Where wildfires destroy buildings in the US relative to the wildland-urban interface and national fire outreach programs. International Journal of Wildland Fire 27: 329-341 https://www.fs.usda.gov/treesearch/pubs/56376

Mockrin, M. H., H. K. Fishler, and S. I. Stewart. 2018. Does wildfire open a policy window? Local government and community adaptation after fire. Environmental Management. 62(2): 210–228 https://www.fs.usda.gov/treesearch/pubs/56375

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Kramer, H. A., V. Butsic, M. H. Mockrin, C. Ramirez-Reyes, P. M. Alexandre, V. C. Radeloff. In review. California post-wildfire rebuilding and new building location reveals limited adaptation. Proceedings of National Academy of Sciences

2. Technical reports (specify whether In Press, accepted for publication, submitted for publication, or planned/in preparation).

Fishler, H. K., M. H. Mockrin, and S. I. Stewart. 2019. "Response and future readiness: Vegetation mitigation after destructive wildfire" In L. Campbell, E. Svendsen, N. Sonti, S. Hines, and D. Maddox (Eds.), Green Readiness, Response, and Recovery: A Collaborative Synthesis. Gen. Tech. Rep. NRS-P-185. Newtown Square, PA: U.S. Department of Agriculture, Forest Service. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs-p-185.pdf

3. Graduate thesis (masters or doctoral)

Fishler, H. K. 2018. Doctoral Thesis in Environmental Sciences. How We've Rebuilt: Collaboration, Community, Institutions, and Adaptation Following Catastrophic Wildland Fire in the United States. Oregon State University, Corvallis, OR https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/f7623g716

4. Conference or symposium abstracts

Mockrin, M. H., S. I. Stewart, H. K. Fishler, P.A. Alexandre, and V. C. Radeloff. April 2015. After the fire: Structure loss, rebuilding, and local policy. Presentation at International Association of Wildland Fires' Human Dimensions of Wildfire Conference, Boise, ID.

> The number of structures destroyed by wildfire in the United States has risen dramatically over the past decade, with approximately 1,300 residences lost annually to wildfire since 2000. In response, fire policy now emphasizes the need to create fire-adapted communities, where the community takes responsibility for its wildfire risk by protecting residents and homes through preparedness and risk mitigation. But is this imperative understood and accepted by communities in the wildland urban interface (WUI)? We do not yet have a solid body of evidence to answer this question, in part because of the delays between wildfire events, regulations, and outcomes on the landscape. Drawing from case studies around the country, we examine communities where wildfires caused significant loss of structures from 2009-2011, in order to determine when and where changes were made in regulations post-fire. We examine changes in zoning and lot sizes, codes that require fire-resistant construction materials and defensible space, and broader planning and open space preservation efforts. We then draw from research on WUI growth and rebuilding to look at where and when post-fire residential growth occurred. By combining information on residential development with our work on post-fire regulation, we will describe how changes in governance can contribute to fire adaptation.

Mockrin, M. H., H. K. Fishler, and S. I. Stewart. April 2017. Opening a Policy Window or a Non-event: Do Wildfires Lead to Local Government Adaptation? Presentation at National Cohesive Wildland Fire Management Strategy Workshop All Hands, All Lands: Implementation Rooted in Science, Reno, NV.

> Becoming a fire-adapted community that can live with wildfire is envisioned as a continuous, iterative process of adaptation. In nine case study sites across the United States we examined how destructive wildfire affected altered progress towards becoming fire-adapted, focusing on the role of WUI regulations (building codes, hazard mitigation standards, zoning, and other local governmental tools used to reduce exposure to wildfire losses). Experience with wildfire and other natural hazards suggests that disasters may open a window of opportunity leading to local government policy changes. However, we found mixed results in our study: for some communities, the fire was a focusing event that led to changes in WUI regulations (for example, modifying building codes). In other communities, destructive fire did not spur adaptation through changes in governmental policy. In some communities, local government officials thought current policies were effective and factors beyond their control such as extreme weather were to blame for structure losses. In other cases, wildfire losses were accepted as a risk of living on the landscape, considered an isolated incident that affected few or was unlikely to be repeated, or enacting regulations was seen as incompatible with local norms and government capacity, We conclude that adaptation to wildfire through WUI regulations depends on multiple factors, including past experience with fire and the geographic extent and scale of the fire event relative to the local community and its government. While communities did not often pursue changes in WUI regulations, experience with wildfire was frequently cited as the impetus for other adaptive responses, such as

improving emergency response or fire suppression, and expanding education and interaction with homeowners, such as Firewise programs or government support for fuel mitigation on private lands.

Kramer, H., Mockrin, M., Radeloff, V. November 2017. How exceptional was the 2017 Tubbs fire? Association for Fire Ecology 2017 Annual Meeting, Orlando, FL.

The Tubbs fire started northeast of Santa Rosa, CA on October 8, 2017 at 9:45pm, and quickly escalated into an extreme event. Fanned by 60mph winds, the fire burned 1,000 buildings overnight, and thousands more before it was extinguished. Housing in the area had increased 7-fold since last burning in 1964, and, if past trends continue, will double by 2050 in this fire prone area. Most threatened homes (71%) in the Tubbs were in the wildland urban interface (WUI), but nearly all remaining homes were in urban areas, uncharacteristic of most wildfires. WUI housing is increasing in CA and across the nation, with 1/3 of CA homes in the WUI in 2010. While the Tubbs fire was unusually destructive and resulted in record loss of life, much of CA is headed in a similar direction, and destruction in fires like the Tubbs may become the norm if policies remain unchanged.

Kramer, H., Butsic, V., Mockrin, M., Ramirez-Reyes, C., Alexandre, P., Radeloff, V. December 2017. Rebuilding and new construction trends after California wildfires. Association for Fire Ecology 2017 Annual Meeting, Orlando, FL.

Destructive wildfires are increasingly prevalent in many parts of the US, yet relatively little is known about long-term housing growth after fires, from both new construction and rebuilding after loss to fire. We investigate the rate of rebuilding and new construction after destructive California wildfires (1970-2010; n=23) and ask how these change over time after fire, if these trends were consistent, and what influences these rates. We found high rebuilding rates (72%) within 20 years after fires, but with high variability (ranging from 13% to 100%). The majority of rebuilding that does occur (67%) was completed within 5 years of the fire, and the vast majority (94%) within 10 years. Most fire perimeters contained more buildings five years after the fire than immediately before, and twice as many (96% growth) 20 years after fire. New construction (versus rebuilding) was the primary driver of 20-year building construction, accounting for 3/4 of the construction since fire. In summary, we find that growth after destructive fires is high, both immediately after fire and 20 years into the future. These findings can be used to inform the longevity of post-fire assistance programs and support changes in policy regarding regulations on building in these areas.

Mockrin, M. H., H. K. Fishler, and S. I. Stewart. October 2018. Limitations to planning and regulation for wildfire hazards: insights from post-wildfire recovery. Presentation at symposium Law, Planning and Wildfire in the Wildland-Urban Interface: The Future of Government and Governance of Disaster in the West, Boise, ID

Becoming a fire-adapted community that can coexist with wildfire is envisioned as a continuous, iterative process of adaptation. Experience with wildfire and other natural hazards suggests that disasters may open a "window of opportunity" leading to local government policy changes. We examined how destructive wildfire affected progress towards becoming fire adapted in eight locations (fires occurred from 2009-2011). Using a combination of interviews, qualitative analysis, and document review we gathered the post-wildfire responses at the community level, and the rationale presented for the tools and actions pursued, as well as the success and failure of responses. Across diverse settings, we found that communities displayed consistent preferences for the most common tools and actions used for wildfire mitigation and planning. Nearly all sites reported changes in wildfire suppression, emergency response, and hazard planning documents. However, few sites reported any changes in governmental legal and policy tools to encourage fire-adapted communities, such as subdivision regulations, road standards, building codes, or defensible space regulations. Where regulatory changes were reported they were modest, either resulting in minor changes or were applicable over small areas. More commonly, we saw no changes in regulations related to wildfire, including communities where destructive WUI fires were novel, and places with long history of wildfires, as well as sites with a range of investment in wildfire-related regulations pre-fire.

Qualitative analysis revealed a number of perceived limitations in pursuing legal and policy tools to reduce wildfire exposure and vulnerability: participants felt such tools were incompatible with local norms and customs, were unenforceable, or that they were unlikely to result in effective reduction in wildfire risk. Instead, respondents emphasized the role of education and voluntary efforts. Respondents also emphasized the importance of education and voluntary compliance in ensuring successful implementation of existing regulations, such as defensible space ordinances. Our findings suggest that legal and policy tools are not commonly adopted as a result of wildfire losses. When they are implemented it is often in coordination with state efforts and requirements and/or in better-resourced communities with planning staff and existing regulation of residential development and the built environment. In suburban settings, informal or non-governmental efforts such as Firewise or home owner association covenants may fill these gaps, but where development is dispersed and neighborhoods less traditional, the form and function of the fire-adapted community must be re-envisioned.

5. Presentations/webinars/other outreach/science delivery materials.

Mockrin, M.H. December 2015. Living in the wildland urban interface: recovery and rebuilding after wildfire. Seminar invited by NRS-08 New York City Urban Field Station (Forest Service and NYC Parks and Recreation office), New York, NY.

Fishler, H. K., M. H. Mockrin, and S. I. Stewart. June 2015. Institutional structure and change after wildfire. Presentation at International Symposium on Society and Resource Management (ISSRM), Charleston, SC.

Kramer, H., Mockrin, M., Alexandre, P., Stewart, S., Radeloff, V. April 2017. Where do buildings burn in the US from wildfire relative to the wildland urban interface and national fire mitigation programs? American Association of Geographers 2017 Annual Meeting, Boston, MA.

Mockrin, M. H., S. I. Stewart, H. K. Fishler, P. Alexandre, H. A. Kramer, and V. C. Radeloff. June 2017. Response and adaptation after wildfire, 2000-2013. Presentation requested by Southwest Fire Science Consortium, a Joint Fire Science Program for science delivery in the Southwest Region. https://www.frames.gov/catalog/24108.

Mockrin gave a similar presentation on wildfire recovery to California Fire Science Consortium, a Joint Fire Science Program for science delivery in California in October 2017. Reworked the presentation above to include California specific material, and address the wildfires of Fall 2017 in Napa and Sonoma counties. October 30, 2017. http://www.cafiresci.org/events-webinars-source/category/recovery-and-adaptation-wui-mockrin

Kramer, H.A. October 2017. The 2017 Tubbs versus the “average” fire: before, during, and after. Presentation requested by the Personal Insurance Federation of California Annual Planning Retreat, Sacramento, CA

Mockrin, M. H., A. Kramer, D. Helmers, H. K. Fishler, V. C. Radeloff, and S. I. Stewart. December 2017. The Wildland-Urban Interface and Rebuilding after Wildfire. Presentation requested by American Planning Association for the Tuesdays at APA seminar series, which was then shared as a podcast. https://www.planning.org/tuesdaysatapa/2017/dc/dec/ Washington DC.

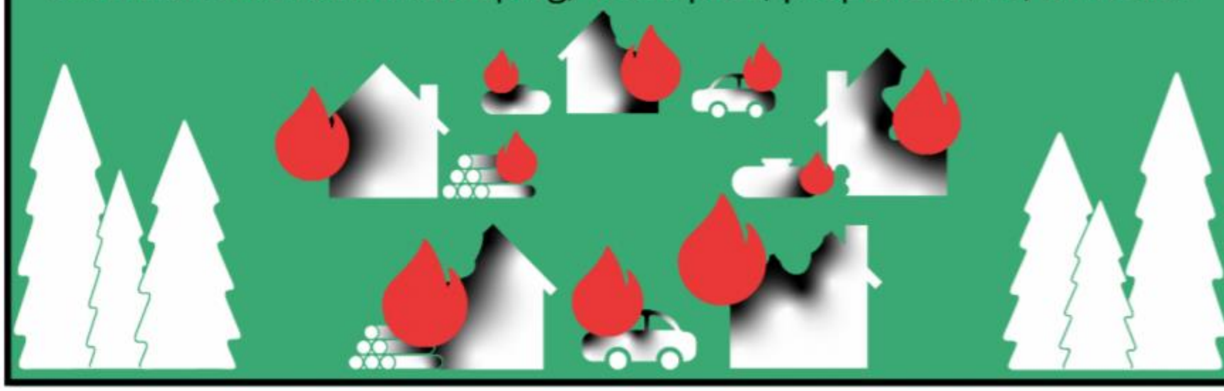
.Mockrin, M. H. 2018. Planning in the wildland-urban interface. Invited panelist at the American Planning Association’s Annual Conference in San Francisco, CA. Then adapted this presentation into a webinar with J. DeAngelis of the American Planning Association, and Molly Mowery of the Community Planning Assistance for Wildfire as a webinar for the Forest Service Urban Connections program on June 12, 2019. Webinar online at https://www.fs.fed.us/research/urban-webinars/planning-in-the-wui/; had 227 participants

News release, newsletter, and infographic about California wildfire losses created by Forest Service R&D: https://www.fs.fed.us/research/docs/newsletter/201910%20October-Newsletter--California-wildfires-dirty-work.pdf & https://www.nrs.fs.fed.us/news/release/wui-interface-intermix

FOREST SERVICE RESEARCH: BY-THE-NUMBERS

50 percent of buildings lost to fire in California in the past 30 years were within an area of the **Wildland-urban Interface** called "interface"—characterized as being near large patches of wildland and having sparse or no wildland vegetation.

This underscores the importance of mitigating human-related fuels such as residential landscaping, wood piles, propane tanks, and cars.



Appendix C: Study sites for Objective A

We refer to sites by a combination of the fire name and the state abbreviation. The wildfire suppression resources we mention are those departments that are present in the area and engaged in wildfire mitigation and management; actual fire responses to these incidents involved a mix of local and outside resources, including state and federal suppression resources, depending on the incident.

Caughlin Ranch, Nevada (NV)

The Caughlin Ranch fire began as an electric ignition on privately owned land in Washoe County, and burned into the city of Reno, destroying 42 homes in November 2011. Washoe County and Reno are growing in population, fueled by access to outdoor amenities and arrival of retirees. Recent development is primarily in subdivisions and planned unit developments (PUDs) around Reno's borders. This fire affected upper to middle income, single family, primary homes on the southwestern outskirts of Reno where residential development abuts county-owned canyons that are not developable because of the terrain. The county has active wildland firefighting teams, while the city fire department concentrates on structure protection. Although there was a long history of WUI fires in the state and Lake Tahoe area, this fire was notable for spreading into Reno, and for occurring in November.

Hwy 31/WG, South Carolina (SC)

The Highway 31 (Hwy 31) fire began with residential debris burning in Horry County and moved into the city of North Myrtle Beach, destroying 76 homes in April 2009. This fire affected middle income, single family homes in a large planned unit development (PUD) with golf courses. Respondents discussed this fire along with the 2013 Windsor Green (WG) fire that destroyed over 100 homes in six condo buildings in Horry County, so we included both fire incidents and jurisdictions in our study. Both fires affected primarily full-time residents. Unincorporated Horry County has grown rapidly in recent decades, with development of large subdivisions and PUDs, driven by access to the beach and popularity with retirees. North Myrtle Beach is mostly developed but can grow via annexation. The county has an active wildland firefighting team, while the city fire department concentrates on structure protection. This area has a long history of wildfires, but previous fires affected open space or timber plantations, before housing development expanded into wildlands. These fires were seen as notable given the number of homes lost, and the speed with which they progressed.

Loco-Healdton, Oklahoma (OK)

The Loco-Healdton fire occurred in April 2009, as a result of malfunctioning power lines, and burned structures in ranch and agricultural lands in Stephens County, and some area in Carter County. Approximately 20 homes were lost, all owned by full-time residents, including modest manufactured homes and trailers, as well as custom homes. The economy in these counties is dominated by energy production and ranching, and land is primarily privately-owned and unincorporated. Housing growth or expansion is not a concern in this area. This part of Oklahoma has a long history of volatile, wind-driven grass fires, and 2009 was a year with substantial wildfire activity across the state, including multiple fires on the day that the Loco-Healdton fire began. Rural volunteer fire departments are responsible for much of the area, with help from Oklahoma Forestry Services wildland fire suppression team when needed. Despite the prevalence of wildland fire, most rural fire departments are trained primarily in structural firefighting.

Monastery, Washington (WA)
The Monastery fire started as result of a tractor-trailer malfunction in unincorporated Klickitat County, destroying 12 homes and numerous outbuildings in September 2011. Most homes in this area are modest primary residences or second homes with a few upscale second or retirement homes mixed in, on 5-20 acre parcels. Homes lost in the fire included five permanent residences, all trailers, and seven secondary homes. Modest parcel subdivision and housing growth have occurred in recent decades, with migrants drawn by natural amenities, but the area's economy remains limited. Most land in this area is privately owned, and is a mixture of grassland and forest. The county is served by multiple volunteer fire districts. Substandard housing and roads make wildland and structural firefighting challenging. Wildfire is a common occurrence in this area, but past fires had been contained or had occurred in ranch lands.

Monument, Arizona (AZ)
The Monument fire occurred in June 2011 (unknown origin), and burned extensively on the Coronado National Monument before spreading to the Coronado National Forest and privately-owned land in Cochise County, burning 62 homes, all primary residences. Homes in the fire area and nearby are a mix of custom built and modular homes on 1-4 acre parcels. Housing in the canyons outside the National Forest has expanded over the past several decades. Fort Huachuca in Sierra Vista drives much of the area's economy and attracts military retirees. The fire area is served by professional fire departments, and federal firefighters are also active in the area. This fire was bigger and more destructive than previous wildfires, which had been contained on federal land.

Possum Kingdom, Texas (TX)
The Possum Kingdom Complex fire (unknown origin) burned 254 homes and outbuildings in the Possum Kingdom Lake resort community in Palo Pinto County, Texas in April 2009. While the county is rural, the manmade lake's 300-mile shoreline is ringed with second homes owned by residents of Dallas-Fort Worth. Homes range from older, modest homes on unpaved roads to upscale, large homes constructed on multiple parcels, in recently developed, gated and paved subdivisions. The Brazos River Authority, a state agency, originally leased lakefront land for development and managed its vegetation. Growth in this area has increased greatly since the development of a local water supply in the early 1990s, and in 2010 residents were able to purchase parcels, so that the area transitioned from state to private ownership. Fire protection is provided by the local volunteer fire department. This complex of fires was considered unusual in the number of homes burned and size of the incident.

Station, California (CA)
The Station fire started in the Angeles National Forest as the result of arson and burned into unincorporated Los Angeles County in August 2009, destroying 89 homes. Approximately 2/3rds of homes lost were along the southern border of the forest, with 32 lost in a forest inholding (Stonyvale/Vogel Flats). Homes were older, modest houses clustered on small parcels, divided between privately-owned homes and Forest Service-owned recreation cabins. Wildfire management is provided by the Angeles National Forest, and structure protection by Los Angeles County Fire Department, which is also active in wildfire mitigation and outreach. The county and this area along the southern border of the Angeles National Forest have had extensive WUI fires in the past, but the Station fire was notable for its size (at over 160,000 acres it was the

largest fire in LA County in decades), and attracted controversy about the Forest Service suppression response.

Wallow, Arizona (AZ)

The Wallow Fire started in May 2011 as an unattended campfire on the Apache-Sitgreaves National Forest and grew to over 500,000 acres (the largest fire in Arizona history), destroying 32 homes, primarily in the unincorporated community of Greer in Apache County. Communities in the southern portion of Apache County are small towns with modest, full-time residences in the lower elevation areas. Summer, vacation, and retiree-owned homes on individual parcels are in heavily wooded slopes above the towns. Housing growth has been modest but steady in this area, with residents drawn by the climate and large federal landholdings (more than 85% of Apache County is in public ownership). Each community has their own fire district, staffed by volunteers, in addition to federal wildfire management resources. This was the largest and most destructive wildfire to occur in this area but many in the community had hosted evacuees from the 2002 Rodeo-Chediski fire, which burned 30 miles to the west.

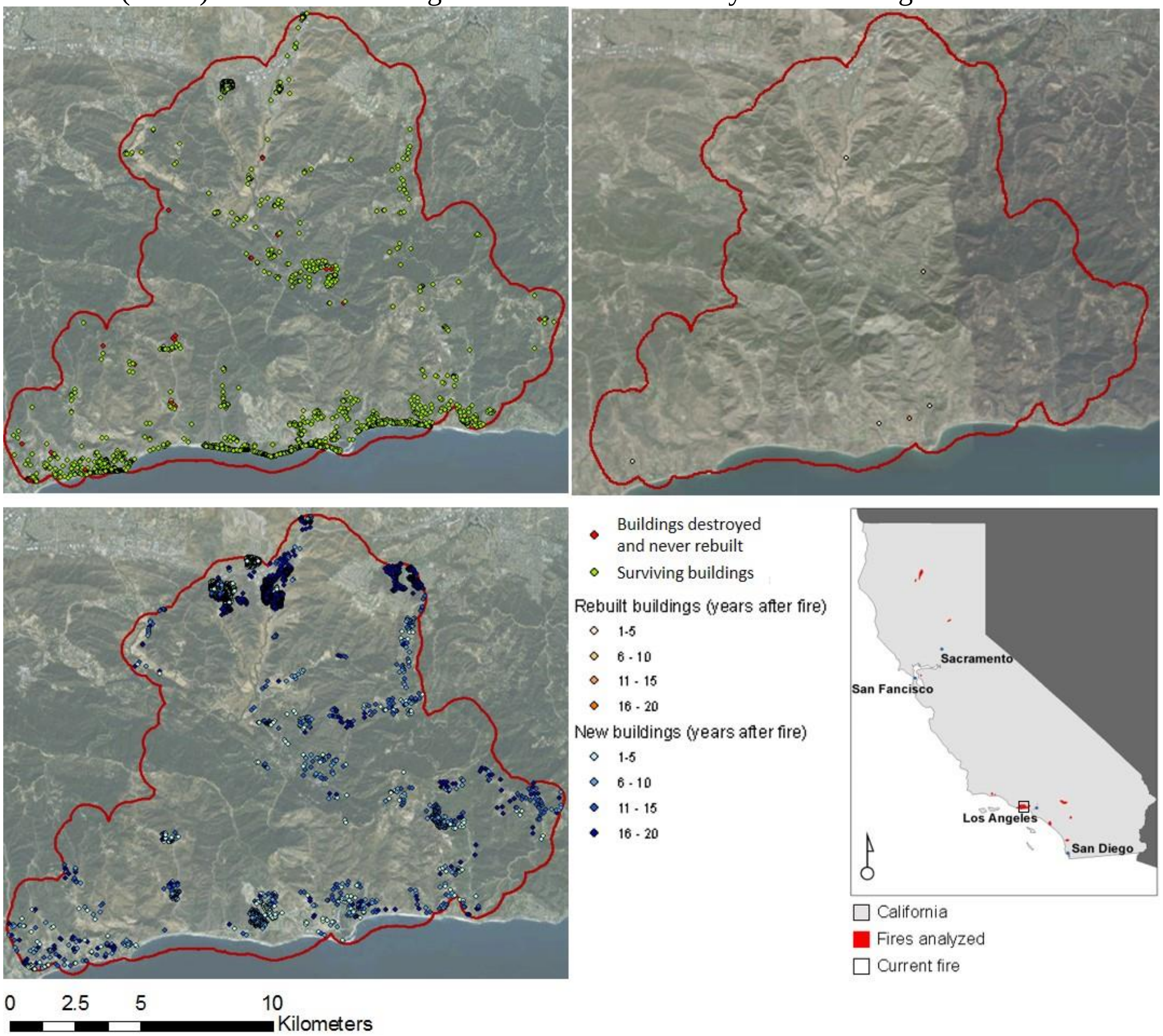
Appendix D: Historical wildfire data.

This appendix describes the wildfires digitized for this research project. Data generated for each wildfire includes digitized buildings for all buildings present before and after wildfire events. These data were gathered by research assistants and are stored both within a spreadsheet and as geospatial data. Wildfire perimeters for each fire below were obtained from California's Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP). Geospatial data on fire perimeters and buildings, as well as a spreadsheet of building locations, will be submitted with this report and to the US Forest Service Research Data Archive.

Wright – 1970

Ignition date of the fire: 9/25/1970

Wright was a big fire with not many buildings destroyed and quickly rebuilt; many new constructions ocurred in the 20 years after the fire. Of 1362 buildings threatened by the Wright Fire, 3% of buildings were destroyed (43; though 103 buildings were theoretically destroyed), and 2472 (187%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	10	15	20	total	1	5	10	15	20	total		
1319	4	1	1	0	6	169	442	418	354	1089	2472	43	103

Imagery used to digitize buildings:

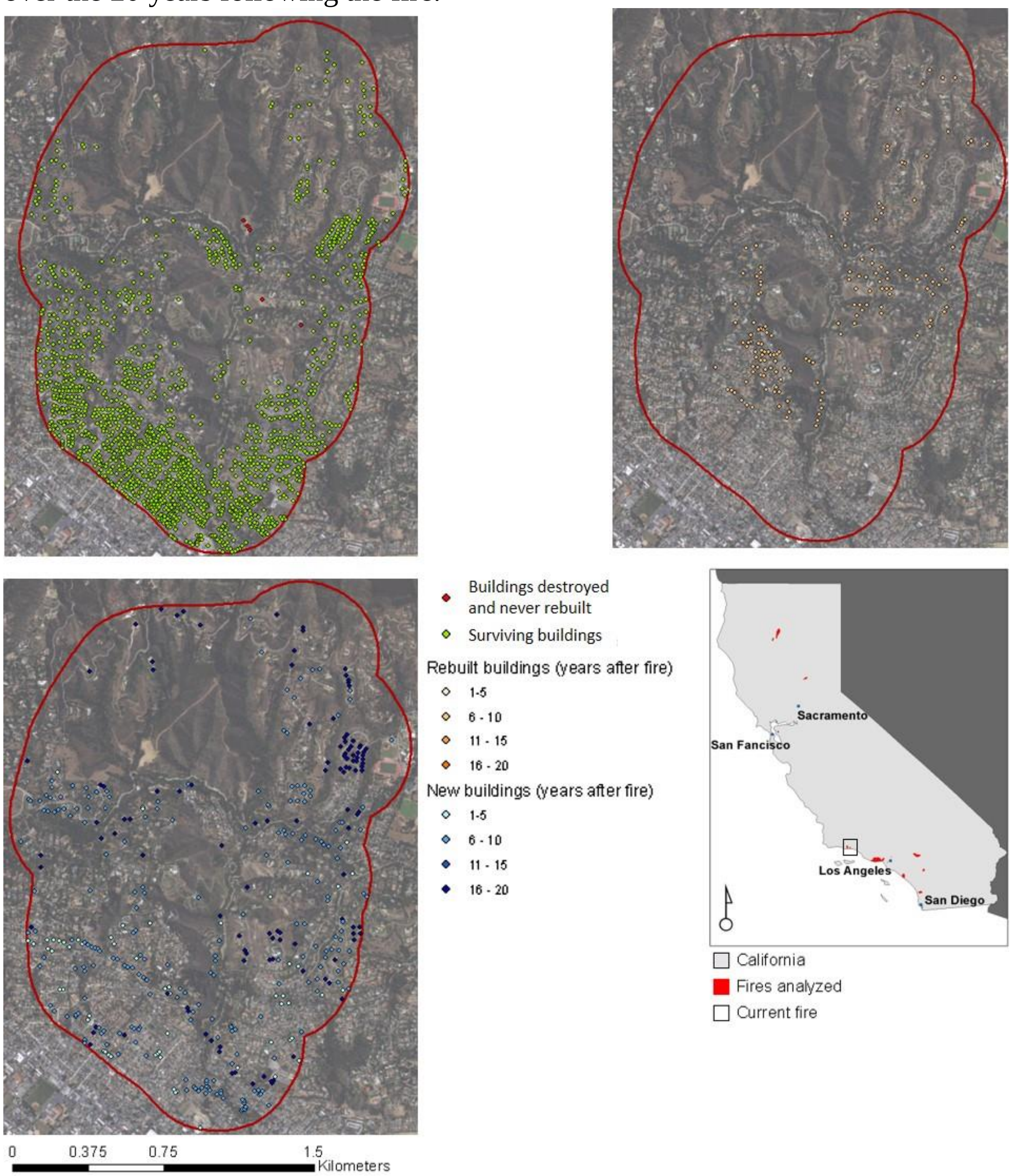
Time step	Imagery dates	Imagery source
1 year pre-fire	1967	NETR
1 year post-fire	1971	AIRS
5 years post-fire	1975	AIRS
10 years post-fire	1980	USGS Aerial photo
15 years post-fire	1985	USGS NHAP
20 years post-fire	7/1989-9/1990	Google Earth

More information about the fire:
http://framework.latimes.com/2010/09/24/chatsworth-malibu-fires/

Sycamore – 1977

Ignition and containment dates of the fire: 7/26/1977 -7/271977

Of 1681 buildings threatened by the Sycamore, 9% of buildings were destroyed (157; though 216-234 buildings were theoretically destroyed), and 393 (26%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

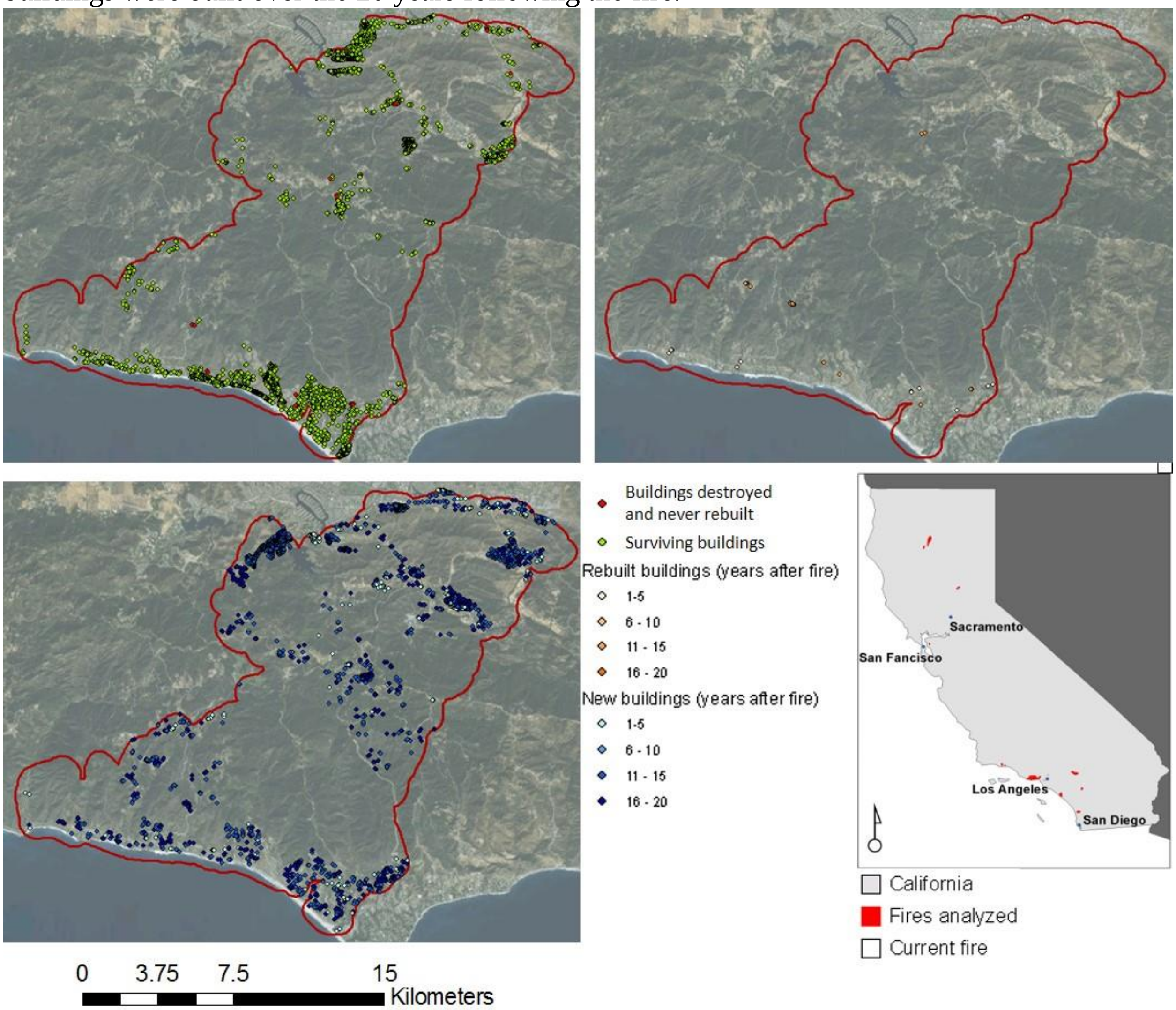
Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	6	10	17	25	total	0	6	10	17	25	total		
1524	129	20	0	3	152	59	118	97	42	77	393	157	1524

Imagery used to digitize buildings:

Time step	Imagery dates	Imagery source
1 year pre-fire	1975	AIRS
1 year post-fire	1977	AIRS
5 years post-fire	1983	AIRS
10 years post-fire	1987	AIRS
15 years post-fire	1994	AIRS
20 years post-fire	2002	Google Earth

More information about the fire:
https://www.researchgate.net/publication/260364095_7-Sycamore_Canyon_Fire_1977
https://www.nytimes.com/1977/07/28/archives/brush-fire-destroys-185-homes-in-santa-barbara-vifsanta-barbara.html

Agoura-Malibu fire – 1978
Ignition and containment dates of the fire: 10/23/1978 – 10/27/1978
Of 2749 buildings threatened by the Agoura-Malibu Firestorm, 2% of buildings were destroyed (60; though 230-484 buildings were theoretically destroyed), and 2159 (80%) additional buildings were built over the 20 years following the fire.



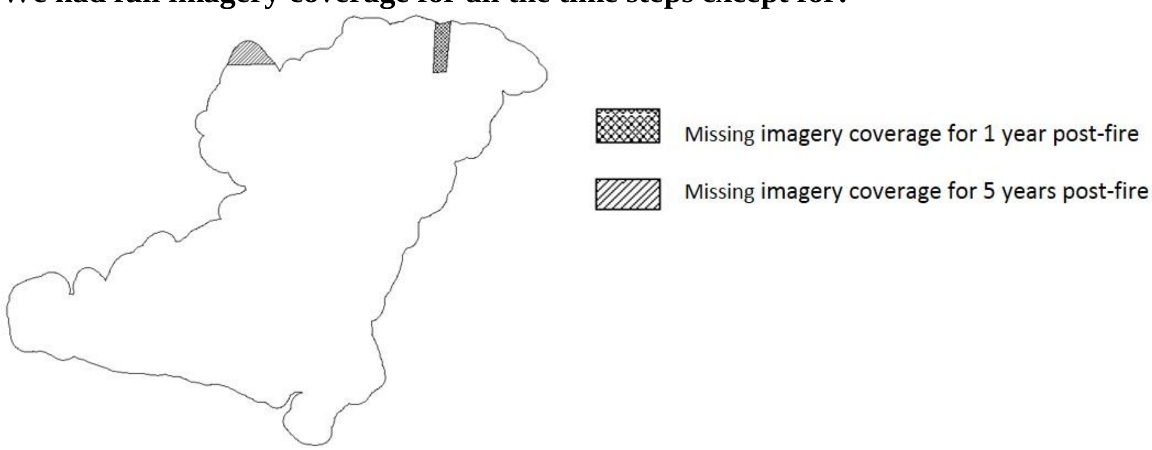
Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	3	11	16	24	total	1	3	11	16	24	total		
2689	14	18	0	1	33	93	164	1136	261	505	2159	60	230-484

Imagery used to digitize buildings:

Time step	Imagery dates	Imagery source
1 year pre-fire	1977	AIRS
1 year post-fire	1979	AIRS (partial coverage)
5 years post-fire	1981	AIRS (partial coverage)
10 years post-fire	1989-1990	USGS DOO
15 years post-fire	06/1994	USGS DOO
20 years post-fire	12/2002	USGS DOO

We had full imagery coverage for all the time steps except for:

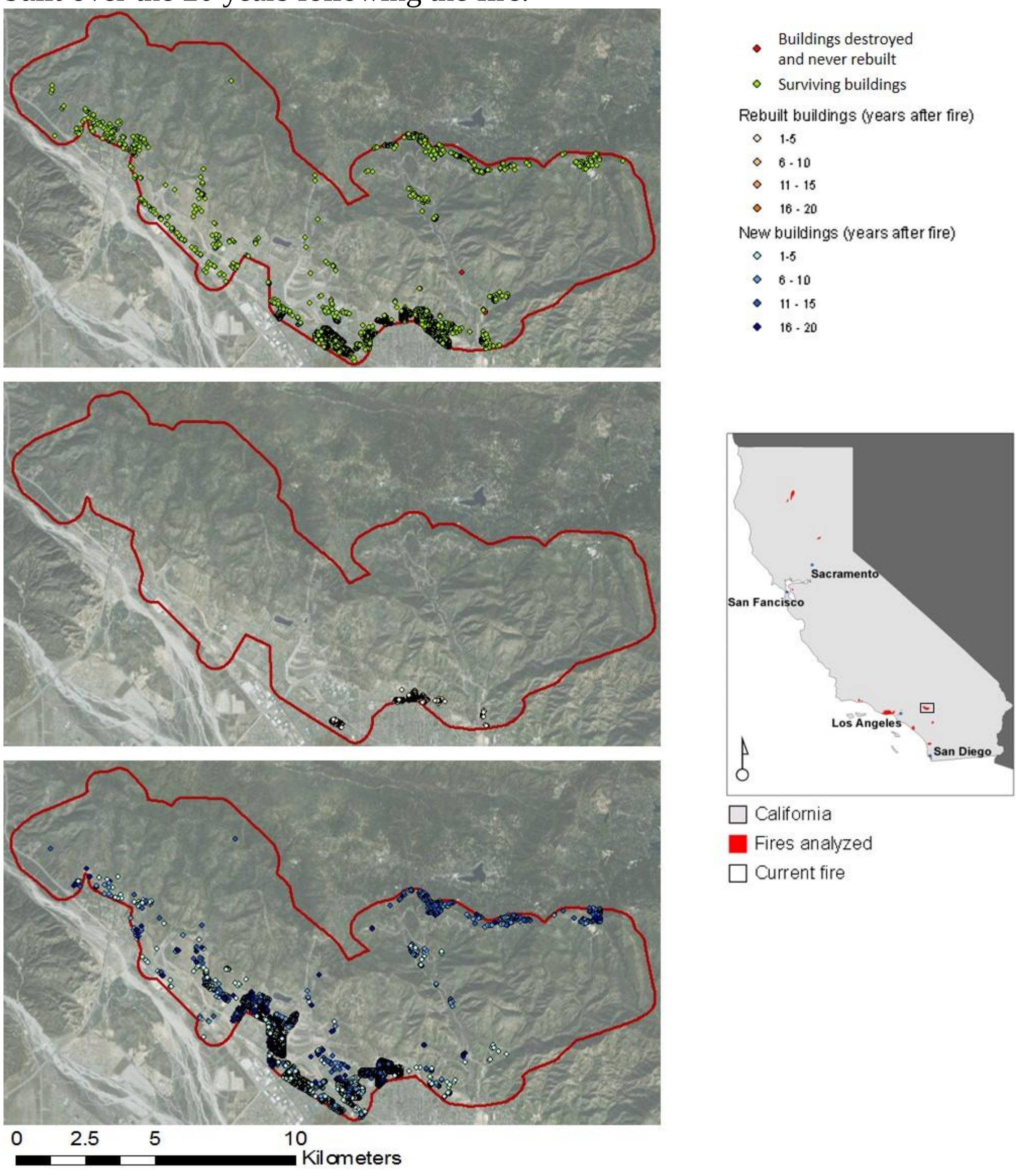


More information about the fire:
https://en.wikipedia.org/wiki/1978_Agoura-Malibu_firestorm

Panorama – 1980

Ignition and containment dates of the fire: 11/24/1980 - 12/1/1980

Of 2340 buildings threatened by the Panorama Fire, 10% of buildings were destroyed (245; though 325 buildings were theoretically destroyed), and 3520 (168%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	9	15	22	total	0	5	9	15	22	total		
2095	243	0	0	0	243	0	1427	987	782	324	3520	245	325

Imagery used to digitize buildings:

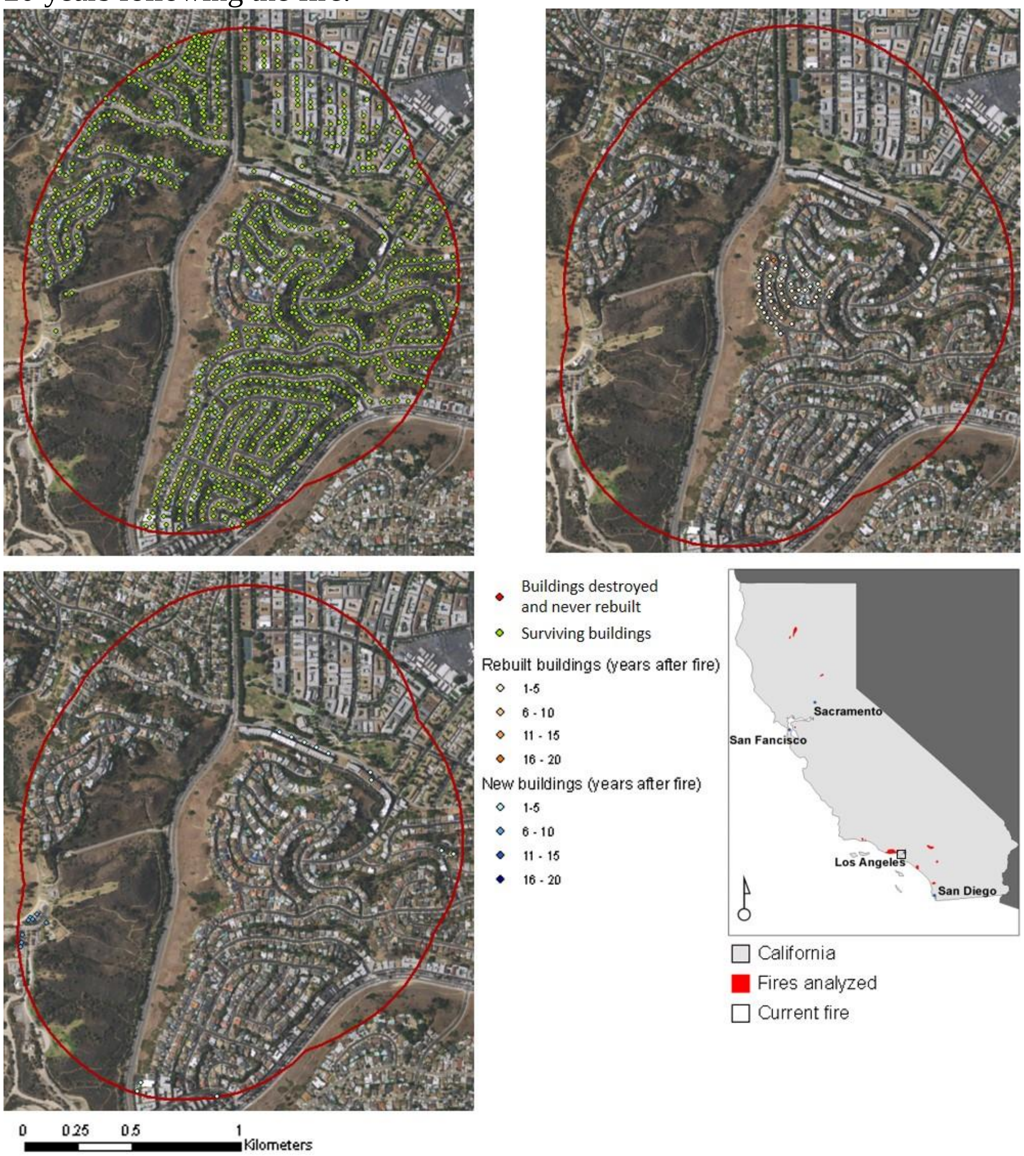
Time step	Imagery dates	Imagery source
1 year pre-fire	1978-79	USGS NETR
1 year post-fire	12/1/1980	USGS Aerial photo
5 years post-fire	08/01/1985	USGS Aerial photo
10 years post-fire	1989-1990	USGS NAPP
15 years post-fire	5/30/1994-10/2/1995	Google Earth
20 years post-fire	5/21/2002	Google Earth

More information about the fire:
http://www.cccarto.com/calwildfire/panorama/fire.html
http://alpenhornnews.com/the-panorama-fire-a-thanksgiving-to-remember-p6628-155.htm

Baldwin Hills – 1985

Ignition and containment dates of the fire: 7/1/1985 - 7/11/1985

Of 1110 buildings threatened by the Baldwin Hills, 6% of buildings were destroyed (67; though 53 buildings were theoretically destroyed), and 11 (1%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	9	17	20	total	0	5	9	17	20	total		
1043	0	67	0	0	67	1	10	0	0	0	11	67	53

Imagery used to digitize buildings:

Time step	Imagery dates	Imagery source
1 year pre-fire	10/20/1980	USGS Aerial photo
1 year post-fire	09/12/1985	USGS NHAP
5 years post-fire	08/22/1989	USGS NAPP
10 years post-fire	1994	Google Earth
15 years post-fire	2002	Google Earth
20 years post-fire	2005	Google Earth

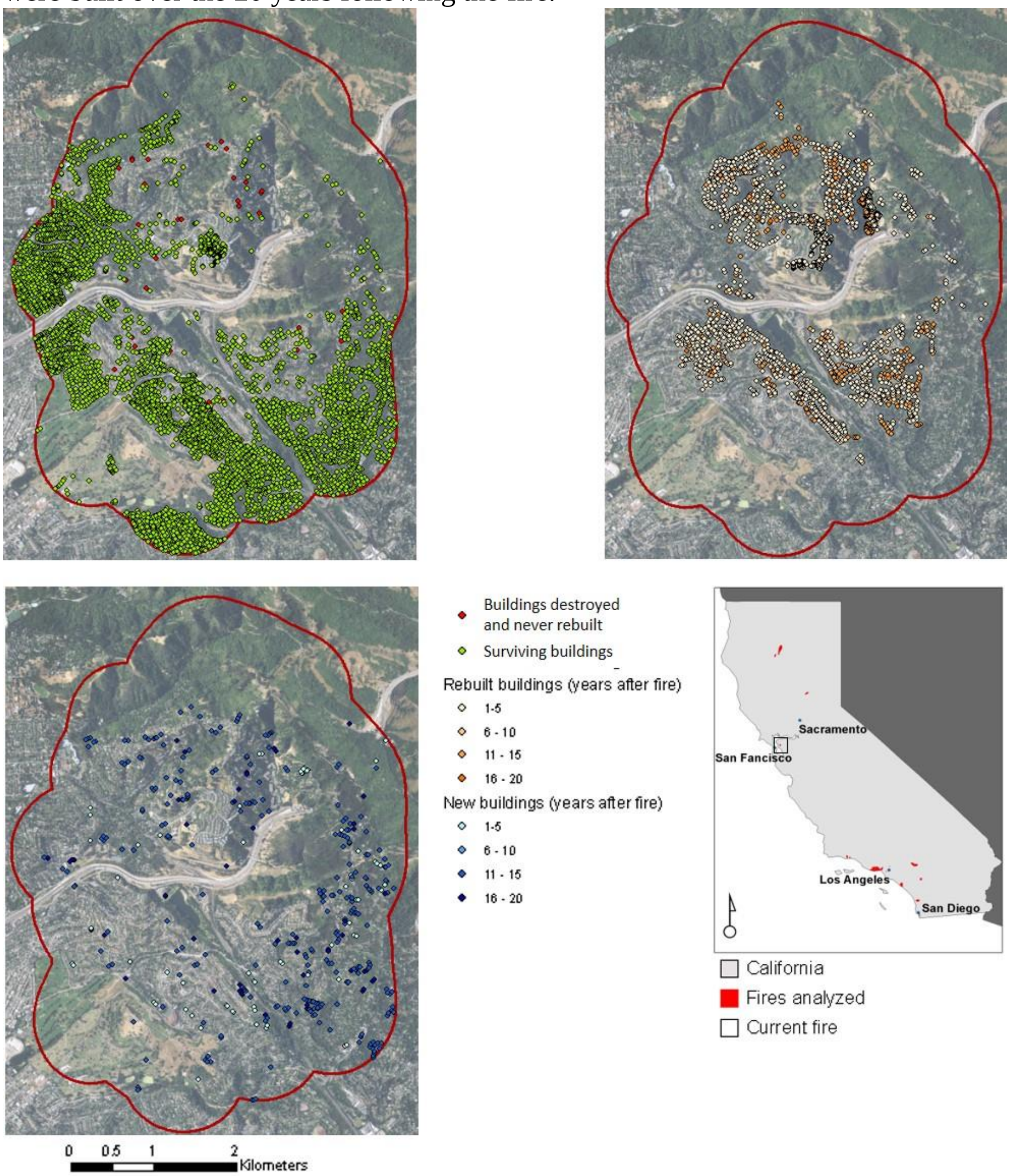
More information about the fire:

http://articles.latimes.com/1985-07-03/news/mn-10192_1_baldwin-hills

Tunnel-Oakland Hills – 1991

Ignition and containment dates of the fire: 10/19/1991 - 10/21/1991

Of 6470 buildings threatened by the Oakland Hills/Tunnel, 32% of buildings were destroyed (2051; though 2900 buildings were theoretically destroyed), and 404 (9%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	11	15	20	total	2	5	11	15	20	total		
4419	1679	279	53	8	2019	1	66	217	67	53	404	2051	2900

Imagery used to digitize buildings:

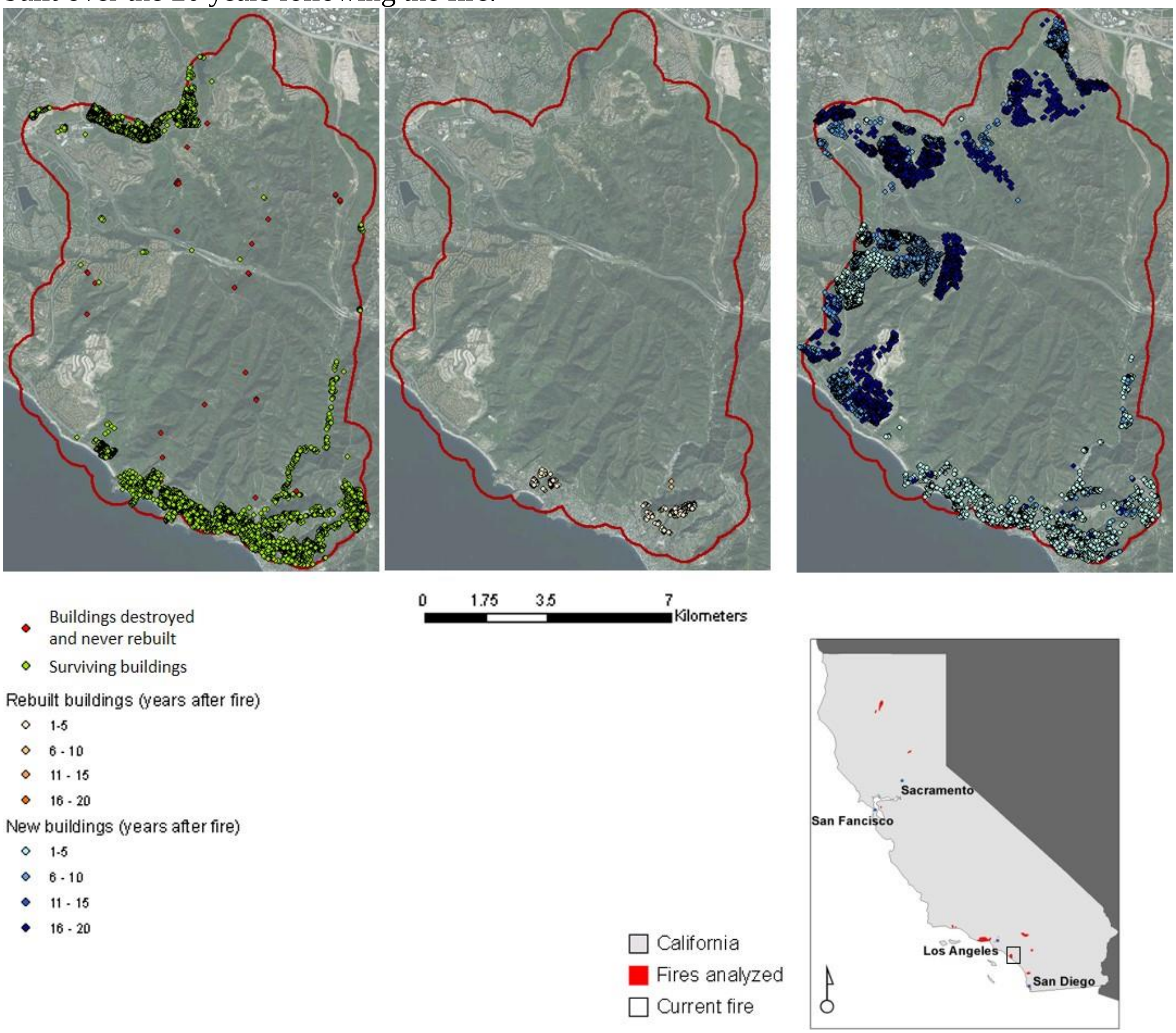
Time step	Imagery dates	Imagery source
1 year pre-fire	2/20/1981	USGS Aerial photo
1 year post-fire	1993	Google Earth
5 years post-fire	1996	USGS NAPP
10 years post-fire	2002	Google Earth
15 years post-fire	2006	Google Earth
20 years post-fire	2011	Google Earth

More information about the fire:
https://www.nytimes.com/1991/10/22/us/fire-in-oakland-ranks-as-worst-in-state-history.html

Laguna – 1993

Ignition and containment dates of the fire: 10/27/1993 - 10/28/1993

Of 4077 buildings threatened by the Laguna fire, 6% of buildings were destroyed (242; though 382-403 buildings were theoretically destroyed), and 5645 (147%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	10	16	20	total	1	5	10	16	20	total		
3835	204	5	0	0	209	1186	550	1581	2232	96	5645	242	448

Imagery used to digitize buildings:

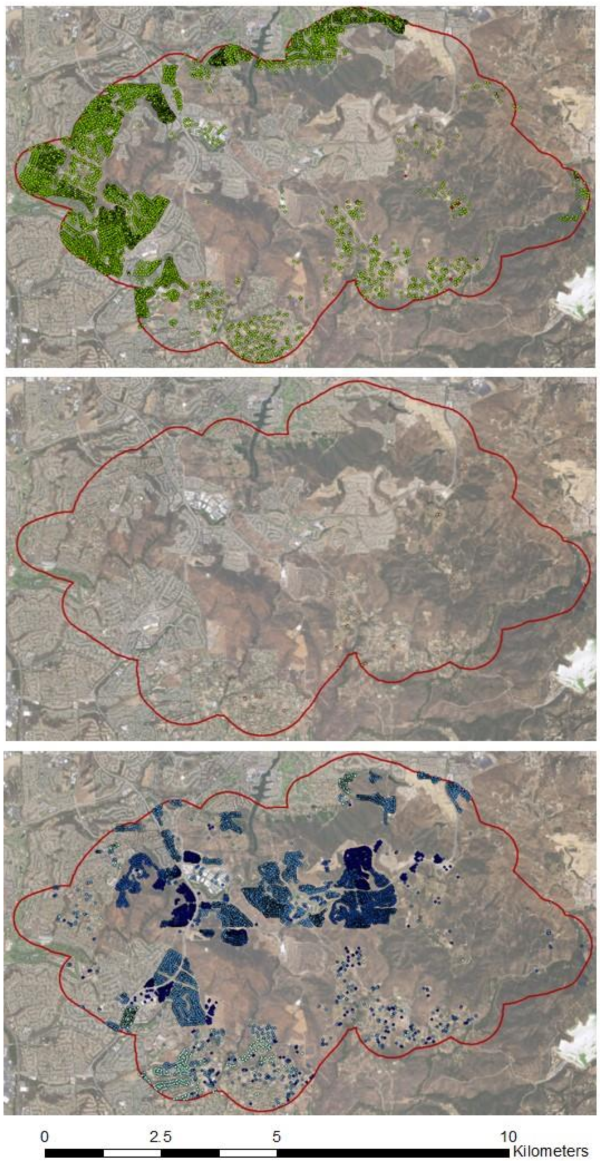
Time step	Imagery dates	Imagery source
1 year pre-fire	1991	USCB MIL Library
1 year post-fire	1994	Google Earth
5 years post-fire	1998	AIRS
10 years post-fire	2003	Google Earth
15 years post-fire	2009	Google Earth
20 years post-fire	2013	Google Earth

More information about the fire:
https://www.portlandoregon.gov/fire/article/324099

Harmony fire – 1996

Ignition and containment dates of the fire: 10/21/1996

Of 6218 buildings threatened by the Harmony Fire, 1% of buildings were destroyed (40; though 110 buildings were theoretically destroyed), and 6341 (103%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	6	10	14& 16	20	total	3	6	10	14& 16	20	total		
6178	22	5	5	0	32	518	1397	1554	2235	637	6341	40	110

Imagery used to digitize buildings:

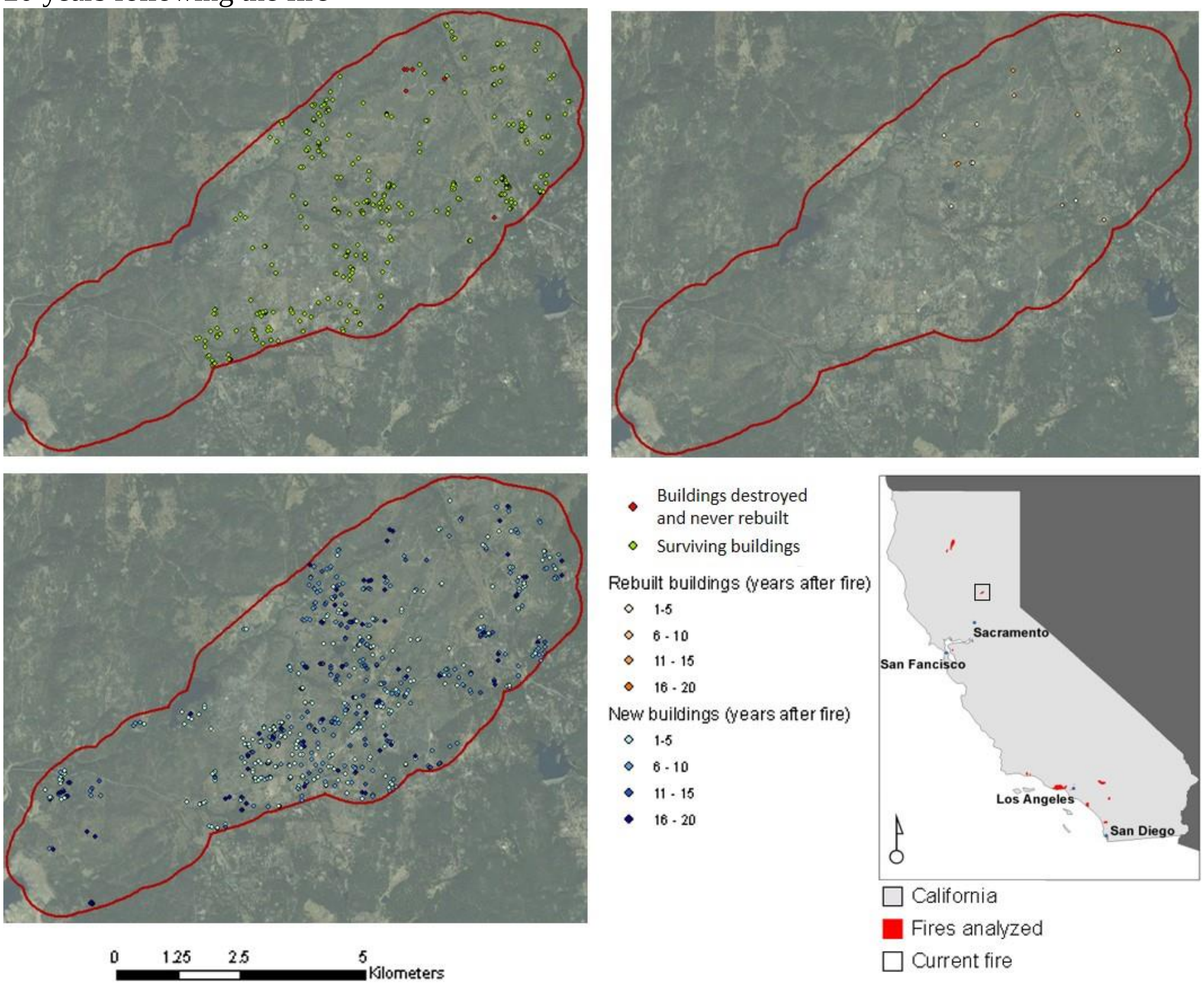
Time step	Imagery dates	Imagery source
1 year pre-fire	1993	USGS DOO
1 year post-fire	02/1999	AIRS
5 years post-fire	2002	AIRS
10 years post-fire	2006	Google Earth
15 years post-fire	2010 & 2012	Google Earth
20 years post-fire	2016	Google Earth

More information about the fire:
http://www.sandiegouniontribune.com/sdut-harmony-fire-left-haunting-memories-prompted-2006oct21-story.html

Williams – 1997

Ignition and containment dates of the fire: 9/27/1997 - 9/30/1997

Of 355 buildings threatened by the Williams, 6% of buildings were destroyed (20; though 85 buildings were theoretically destroyed), and 688 (205%) additional buildings were built over the 20 years following the fire



Digitized buildings:

Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	6	10	14	18	total	1	6	10	14	18	total		
335	6	6	2	0	14	157	129	232	75	95	688	20	85

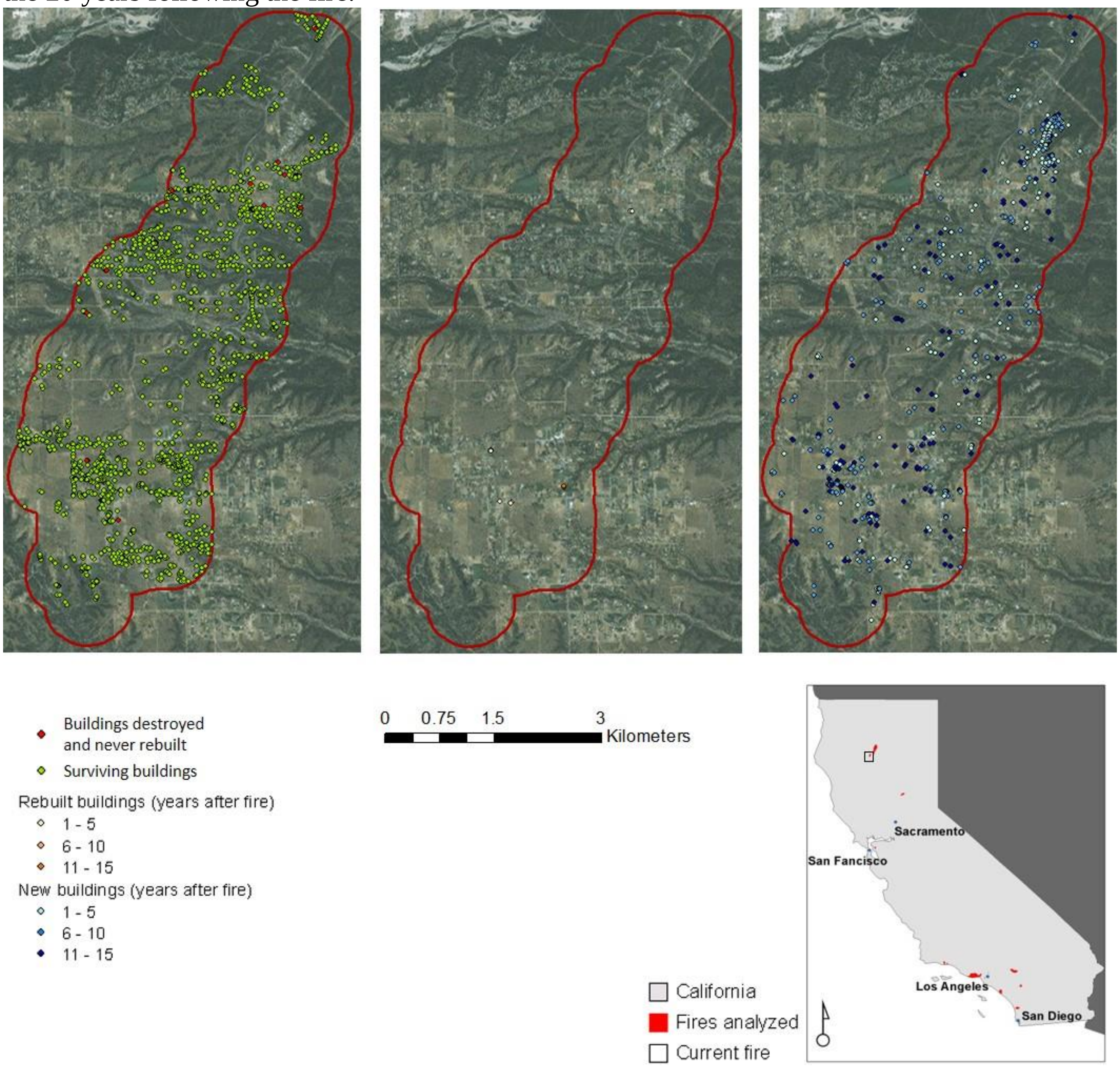
Imagery used to digitize buildings:

Time step	Imagery dates	Imagery source
1 year pre-fire	1993	USGS DOQ and NAPP
1 year post-fire	1998	Google Earth
5 years post-fire	2003	Google Earth
10 years post-fire	2007	Google Earth
15 years post-fire	2011	Google Earth
20 years post-fire	2015	Google Earth

Canyon 4– 1999

Ignition and containment dates of the fire: 9/26/1999 - 9/27/1999

Of 1484 buildings threatened by the Canyon 4 Fire, 1% of buildings were destroyed (21; though 64 buildings were theoretically destroyed), and 470 (32%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

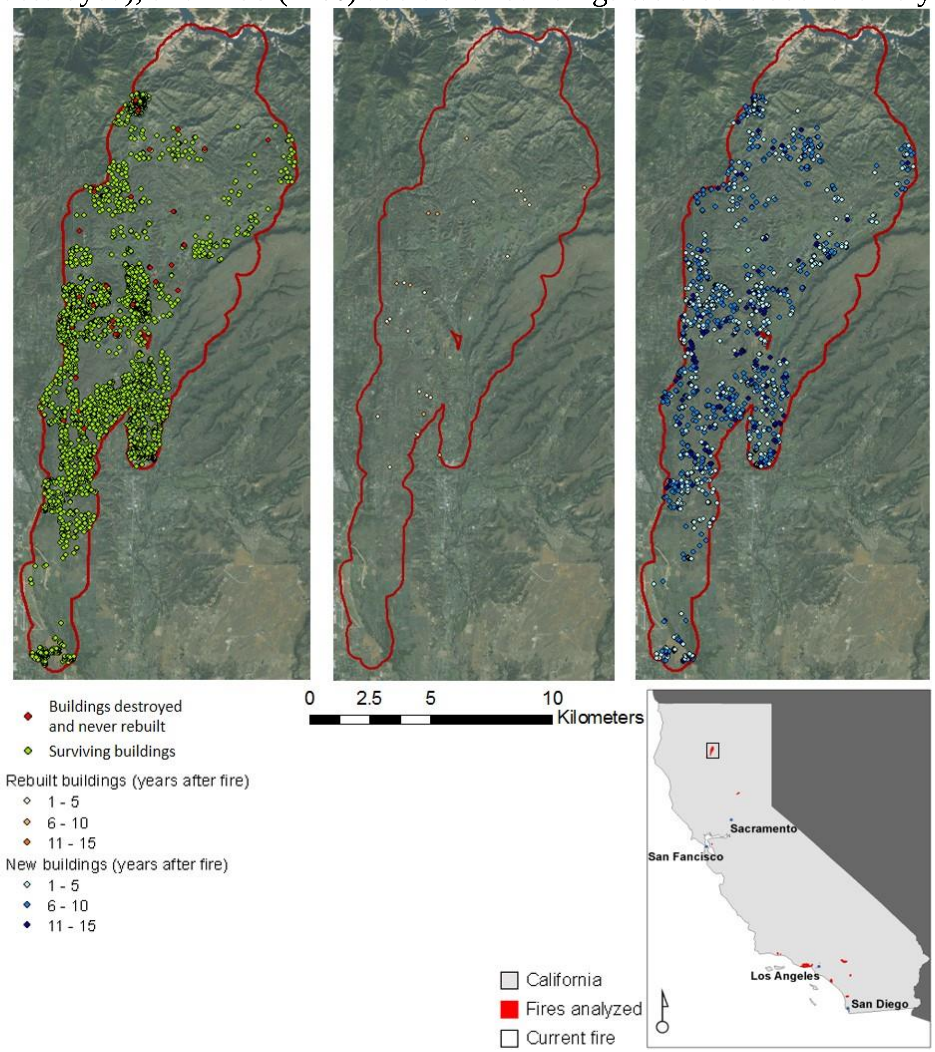
Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	10	16	N/A	total	1	5	10	16	N/A	total		
1463	7	1	1	N/A	9	11	146	179	134	N/A	470	21	64

Imagery used to digitize buildings:

Time step	Imagery dates	Imagery source
1 year pre-fire	8/11/1998	USGS NAPP
1 year post-fire	2000	IKONOS
5 years post-fire	7/30/2004	Google Earth
10 years post-fire	6/5/2009	Google Earth
15 years post-fire	4/5/2015	Google Earth
20 years post-fire	N/A	N/A

More information about the fire:
http://www.fire.ca.gov/communications/downloads/fact_sheets/99FireSeasonSum.pdf
http://www.redding.com/news/massive-fires-nothing-new-in-north-state-hundreds-of-homes-lost-since-1992-ep-375029897-354340011.html

Jones fire – 1999
Ignition and containment dates of the fire: 10/16/1999 - 10/30/1999
Jones was a big fire with not many buildings destroyed and quickly rebuilt; new construction mostly shortly after fire, and fairly dispersed. A 20 year post fire image was not used in the analysis. Of 2977 buildings threatened by the Jones Fire, 2% of buildings were destroyed (59; though 100 or 954 (from different sources – see sources below) buildings were theoretically destroyed), and 1293 (44%) additional buildings were built over the 20 years following the fire.



Digitized buildings:

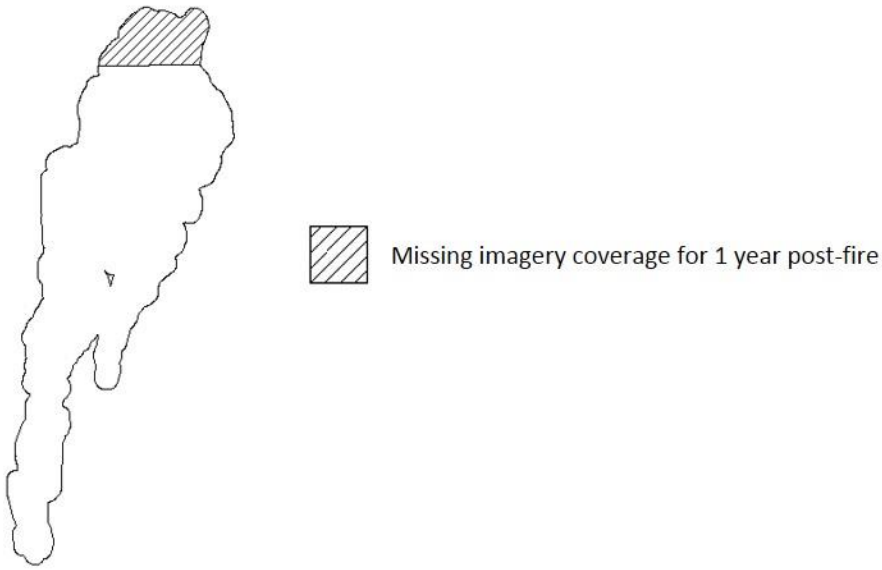
Survived	Rebuilt - years after fire					New - years after fire						Total digitized destroyed	Reported buildings destroyed
	5	10	14& 15	N/A	total	1-2	5	10	14& 15	N/A	total		
2918	20	9	0	N/A	29	274	310	529	180	N/A	1293	59	954

Imagery used to digitize buildings:

Time step Imagery dates Imagery source

1 year pre-fire	9/9/1998	Google Earth
1 year post-fire	12/17/2000 and 3/23/2001	Google Earth (partial coverage)
5 years post-fire	7/30/2004	Google Earth
10 years post-fire	6/5/2009	Google Earth
15 years post-fire	8/27/2013 and 2/21/2014	Google Earth
20 years post-fire	N/A	N/A

We had full imagery coverage for all the time steps except for:



More information about the fire:
http://www.fire.ca.gov/communications/downloads/fact_sheets/99FireSeasonSum.pdf
http://articles.latimes.com/1999/oct/18/news/mn-23592